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Short Communication

Contrasting patterns of the extreme drought episodes of 2005, 2010 and 2015 in the Amazon Basin

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ABSTRACT: Future climate scenarios point to an increase in the frequency of extreme droughts events, even in humid biomes. Throughout the 21st century, large areas of the Amazon basin experienced the most severe droughts ever recorded with special emphasis on the 2005 and 2010 events due to their severity and extent. Currently, there is an increased demand to understand the geographic extent and seasonal variability of climate variables during drought events, especially with respect to the social and environmental impacts. In this study, we aim to compare the observed climate conditions during the drought episodes of 2005, 2010 and 2015. We perform a detailed assessment of the measured precipitation, land-surface temperature (LST) and solar radiation anomalies. We provide evidence that the anomalous precipitation deficit during 2015 exceeded the amplitude and spatial extent of the previous events, affecting more than 80% of Amazon basin, particularly the eastern portion. The pronounced lack of rainfall availability during late spring and early summer, coincident with radiation and temperature surpluses during these years are significant and notable. Changed meteorological spatial patterns were observed, with precipitation and radiation being the most prominent parameters in 2005, whereas precipitation and LST were most relevant in 2010. Understanding the behaviour and interactions of pertinent meteorological variables, as well as identifying similar or divergent patterns over the region during distinct extreme events, is essential for the improvement of our knowledge of Amazon forest vulnerability to climate fluctuation changes.

KEY WORDS Amazon Basin; drought; precipitation; LST; solar radiation

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1. Introduction

Drought is a natural hazard caused by the extreme persistence of a precipitation deficit that occurs in almost all climate zones, even in those with high precipitation rates such as Amazonia (González and Valdés, 2006; Mishra and Singh, 2010). Future scenarios indicate that climate change will likely increase the global risk of extreme drought events both in humid and arid regions. Several global and regional climate models point to a warmer future for South America, with air temperatures increasing between 2 and 5 °C by 2100 (IPCC, 2014). Increased temperatures may induce increased evapotranspiration in tropical regions, reducing the amount of soil moisture, even if precipitation does not vary significantly (Salazar *et al.,* 2007). In addition, changes in land use, as well as biomass burning associated with increased forest fires and the subsequent injection of aerosols into the atmosphere, may affect the beginning of the rainy season and the amount of precipitation in Amazonia (Andreae *et al.,* 2004; Bevan *et al.,* 2009). Reductions in rainfall are expected over the 21st century especially in eastern and southwestern Amazonia (Salazar *et al.,* 2007; Marengo and Espinoza, 2016), therefore projecting an intensification of extreme events such as droughts (Guimberteau *et al.,* 2013; Duffy *et al.,* 2015).

There are two well-known mechanisms responsible for the interannual and spatial variability of precipitation in the Amazon basin (AB), namely, the El Niño–Southern Oscillation (ENSO), and the tropical North Atlantic sea surface temperature (TNA-SST) anomalies (Marengo *et al.,* 2008; Yoon and Zeng, 2010). An anomalous warming of the TNA-SSTs is related to (i) the northward displacement of the Intertropical Convergence Zone (ITCZ), (ii) changes in the north–south divergent circulation and (iii) the weakening of the northeast trade winds and moisture flux from the TNA-SST; leading to less overall precipitation over the southern AB (Zeng *et al.,* 2008; Marengo and Espinoza, 2016). In contrast, ENSO phases induce anomalies in the east–west Walker circulation with convection

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over the warmer waters in the central Pacific and subsidence that inhibits rainfall over most of central and eastern Amazonia (Grimm, 2003; Andreoli *et al.,* 2016; Tedeschi and Collins, 2016; Tedeschi *et al.,* 2016).

During the last century, the AB has experienced several extreme droughts with subsequent environmental, climatic and social-economic impacts (Marengo, 2009). It has been suggested that these events are responsible for significant modifications of the ecosystem's carbon budgets due to tree mortality (Phillips *et al.,* 2009; Lewis *et al.,* 2011; Marengo *et al.,* 2011), as well as modified water resources (Cox *et al.,* 2008) and fire occurrences (Aragão *et al.,* 2007; Nepstad *et al.,* 2008). Despite the local population being well adapted to rainfall variability, recent, consecutive extreme events have disturbed the social-economic resilience, thereby increasing vulnerabilities (Pinho *et al.,* 2015). At the beginning of the 21st Century, the region suffered two unprecedented drought events in 2005 and 2010 (Marengo and Espinoza, 2016). In the case of the 2005 episode, large sectors of the western AB were affected by elevated warming in the Atlantic and reported one of the most intense droughts of the previous 100 years (Marengo *et al.,* 2008). For the 2010 event, the AB suffered the influences of temperature increments of both the Pacific and Atlantic oceans, resulting in an even more severe drought than that observed in the year of 2005 (Lewis *et al.,* 2011).

These recent events have opened discussions on the increase of the drought frequency in the AB, with consideration to the impacts on ecosystems, human activities and climate (Aragão *et al.,* 2007; Phillips *et al.,* 2009; Lewis *et al.,* 2011; Coelho *et al.,* 2012). A strong El Niño event was reported during 2015, resulting in drier conditions over Amazonia compared to the ENSO-related drought events of 1982/83 and 1997/98 (Jiménez-Muñoz *et al.,* 2016). However, to the best of our knowledge, there is no study that compares the 2015 drought with the 2005 and 2010 episodes, which were previously classified as 'once in a century' extreme events. Therefore, the objective of this work is to conduct a comparative analysis of the Amazonia drought episodes of 2015, 2010 and 2005. We discuss anomalous meteorological parameters and map their geographic extent and temporal distributions. Though precipitation deficit is often assumed to be the main driver of drought, higher land-surface temperatures (LST) increase transpiration and evapotranspiration, which in turn, decreases the soil moisture and affects the vegetation (Lewis *et al.,* 2011; Choat *et al.,* 2012; Rowland *et al.,* 2015). In addition, increased solar radiation might initially increase vegetation productivity, but in prolonged drought conditions, it might eventually produce negative effects, and the threshold remains unknown (Hilker *et al.,* 2014).

Therefore, this study aims to discriminate the roles played by precipitation (P), land-surface temperature (L) and solar radiation (R) as drought drivers with the purpose of understanding their behaviour and interactions and identifying similar and divergent patterns of different extreme events over the region.

Table 1. Definition of the four considered classes, taking into account the cumulative and distinctive impacts of each meteorological variable during the three drought events.

Classes	Meteorological variables		
	Min P	Max L	Max R
C1	X	X	X
C2	X		X
C3	X	X	
C4	X		

The symbol X means that a specific meteorological variable [precipitation (P), LST (L) and/or solar radiation (R)] is included in each class.

2. Data and methods

Monthly precipitation data were extracted from the Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) 3B43 Product V7 (Huffman *et al.,* 2007), at 0.25° resolution. Monthly values of LST at 0.05° resolution were obtained from Moderate Resolution Imaging Spectroradiometer (MODIS) onboard Terra satellite, specifically the Land Surface Temperature and Emissivity Monthly L3 Global 0.05Deg CMG v5 (MOD11C3) product (Wan, 2008). Monthly means of incoming shortwave radiation flux at the surface were extracted from the National Aeronautics and Space Administration Modern-Era Retrospective Analysis for Research and Applications Reanalyzes (NASA/MERRA) (Rienecker *et al.,* 2011) at 0.5° resolution.

The influence of meteorological conditions on drought occurrences is established by means of composite analysis performed over the periods characterized by anomalous values of precipitation, LST, and solar radiation. All datasets from the 15-year period spanning 2000 to 2015 were resampled using the nearest neighbour technique to match the 0.25° latitude by 0.25° longitude grid of TRMM. We computed 4-month composites of P, L and R, defined as the averages of February, March, April and May (FMAM); June, July, August and September (JJAS) and October, November, December and January (ONDJ), for each grid point (Hasler and Avissar, 2007). We used standardized anomalies for 4-month composites (henceforth temporal composites) over the entire period in order to characterize the magnitude and temporal evolution of each drought episode within a historical context. Furthermore, we have identified temporal composites characterized by extreme deficits (surpluses) of precipitation (LST and solar radiation) measured as below (above) standard deviation (SD) values of −1 (+1) and summarized the spatial patterns in four classes, where the cumulative occurrence of the extremes was observed (Table 1). Consequently, the spatial patterns of the defined four classes summarize the distinctive impact of each meteorological variable during the three drought events. Whereas the class C1 represents the region controlled by the simultaneous occurrence of a precipitation minimum and solar radiation and temperature maxima, the class C4 corresponds to the area affected by the minimum of precipitation.

Table 2. Fraction (%) of the Amazon Basin area affected by historical anomalous values of precipitation (P), LST (L) and solar radiation (R).

	2005			2010			2015		
	FMAM (%)	JJAS (%)	ONDJ (%)	FMAM (%)	JJAS (%)	ONDJ (%)	FMAM (%)	JJAS (%)	ONDJ (%)
P	3.5%	37.9%	2.0%	6.1%	42.9%	9.6%	1.2%	29.3%	80.1%
L	19.5%	10.3%	6.8%	59.6%	42.0%	10.5%	16.1%	83.0%	90.9%
R	31.7%	78.4%	6.5%	5.2%	8.0%	0.1%	25.5%	28.0%	49.6%

Anomalous values, based on the standardized anomalies for each temporal composite over the 15-year period (2000–2015), are defined as follows: below −1 SD for precipitation and above +1 SD for LST and radiation.

3. Results and discussion

For the three drought episodes, the anomalous conditions for each drought year are represented by the percentage of the AB affected by historically anomalous values of precipitation, LST and solar radiation (Table 2). Beside the differences among each variable, the three events differed markedly in terms of area and temporal coverage. A precipitation deficit was evident in JJAS for 2005 and 2010, while in 2015 the most dry conditions were observed in ONDJ, corroborating previous studies which highlighted the expected TNA-SST and ENSO influences on Amazon rainfall (Marengo *et al.,* 2008; Espinoza *et al.,* 2011; Lewis *et al.,* 2011; Xu *et al.,* 2011; Coelho *et al.,* 2012; Jiménez-Muñoz *et al.,* 2016).

Figure 1 displays the spatial patterns of P, L and R standardized anomalies for each extreme temporal composite (JJAS in the case of 2005 and 2010 and ONDJ in the case of 2015); record-breaking minimum (maximum) values of precipitation (LST and solar radiation) are demarked by contour lines. For 2005 and 2010, both the first and second minima (maxima) were selected to avoid overlapping the two JJAS droughts. Evaluating the precipitation standardized anomalies revealed that the AB suffered a larger precipitation deficit in 2015 compared to 2010 and 2005. Moreover, the area affected by the precipitation deficit in 2015 was almost double (+3.4 SD) that of the previous droughts (+1.8 SD and +2.1 SD in 2005 and 2010, respectively).

Negative precipitation anomalies were observed from the start of the rainy season in December 2004 and early 2005, and intensified after April 2005, resulting in an extreme dry season in 2005 that affected 37.9% of the AB in JJAS (Table 2). The core of the 2005 precipitation deficit was mainly over the western and southwestern part of the AB whereas the eastern sector was less impacted exhibiting normal conditions and positive rainfall anomalies. Such spatial patterns seen in AB are consistent with the atmospheric features resulting from warmer TNA-SSA (Yoon and Zeng, 2010; Andreoli *et al.,* 2016; Tedeschi and Collins, 2016; Tedeschi *et al.,* 2016), leading to weak upward motion and subsidence over the central-western and southwestern AB and convective activity over the central and eastern AB (Zeng *et al.,* 2008; Espinoza *et al.,* 2011; Marengo and Espinoza, 2016).

Similar to 2005, the drought event of 2010 was associated with reduced rainfall over the west and southwest AB but also over the southeast sector, thus affecting a larger area (Figure 1, top central panel). The 2010 episode was considered more severe than 2005 and was related to the successive occurrence of an El Niño event and a strong warming of the TNA-SST (Espinoza *et al.,* 2011; Lewis *et al.,* 2011; Marengo *et al.,* 2011). Although this event began through an El Niño event during the austral summer of early 2010, it continued to intensify because of the TNA-SST warming in the austral winter and the maximum disturbed area (42.9%) occurred in JJAS (Table 2), which is consistent with the obtained spatial patterns of precipitation (Figure 1, top middle panel). Despite the different AB boundaries used in the present work, our results are in accordance with previous representations of the greatest spatial extent of the 2010 drought in comparison to 2005 (Aragão *et al.,* 2007; Marengo *et al.,* 2008; Espinoza *et al.,* 2011; Lewis *et al.,* 2011; Xu *et al.,* 2011; Coelho *et al.,* 2012).

The El Niño episode of 2015–2016 was considered to be one of the strongest events observed since 1950 (Xue and Kumar, 2016; Barnard *et al.,* 2017), leading to widespread precipitation deficits for almost the entire AB, in particular the eastern area (Figure 1, top right panel). The Pacific's influence on Amazon rainfall decreased towards the west and south of the basin, as observed in our results. This feature highlights the strong and extensive impacts of El Niño–induced droughts on the Basin, particularly during the rainy season (Yoon and Zeng, 2010). Moreover, the El Niño of 2015–2016 developed late in 2014 with the maximum value of NINO 3.4 observed in November 2015 (approximately 3 °C), although it remained strong until January 2016 (Xue and Kumar, 2016; Barnard *et al.,* 2017); consequently, the higher percentage of affected area (80.1%) occurred in ONDJ.

In the case of both the 2005 and 2010 events, precipitation values returned to normal conditions by the following temporal composites (Table 2). This seems to be related to the greatest TNA-SST influence occurring during the dry season (Yoon and Zeng, 2010). In the case of 2010, the drought episode was followed by a rapid transition to wet conditions related with the strong 2010–2011 La Niña event (October 2010 to March 2011). The results related to the post-precipitation recovery for the drought of 2015 (not shown) could be related to the weakening of 2015–2016 El Niño after the austral summer and a transition to La Niña–conditions observed around the fall of 2016 (Xue and Kumar, 2016).

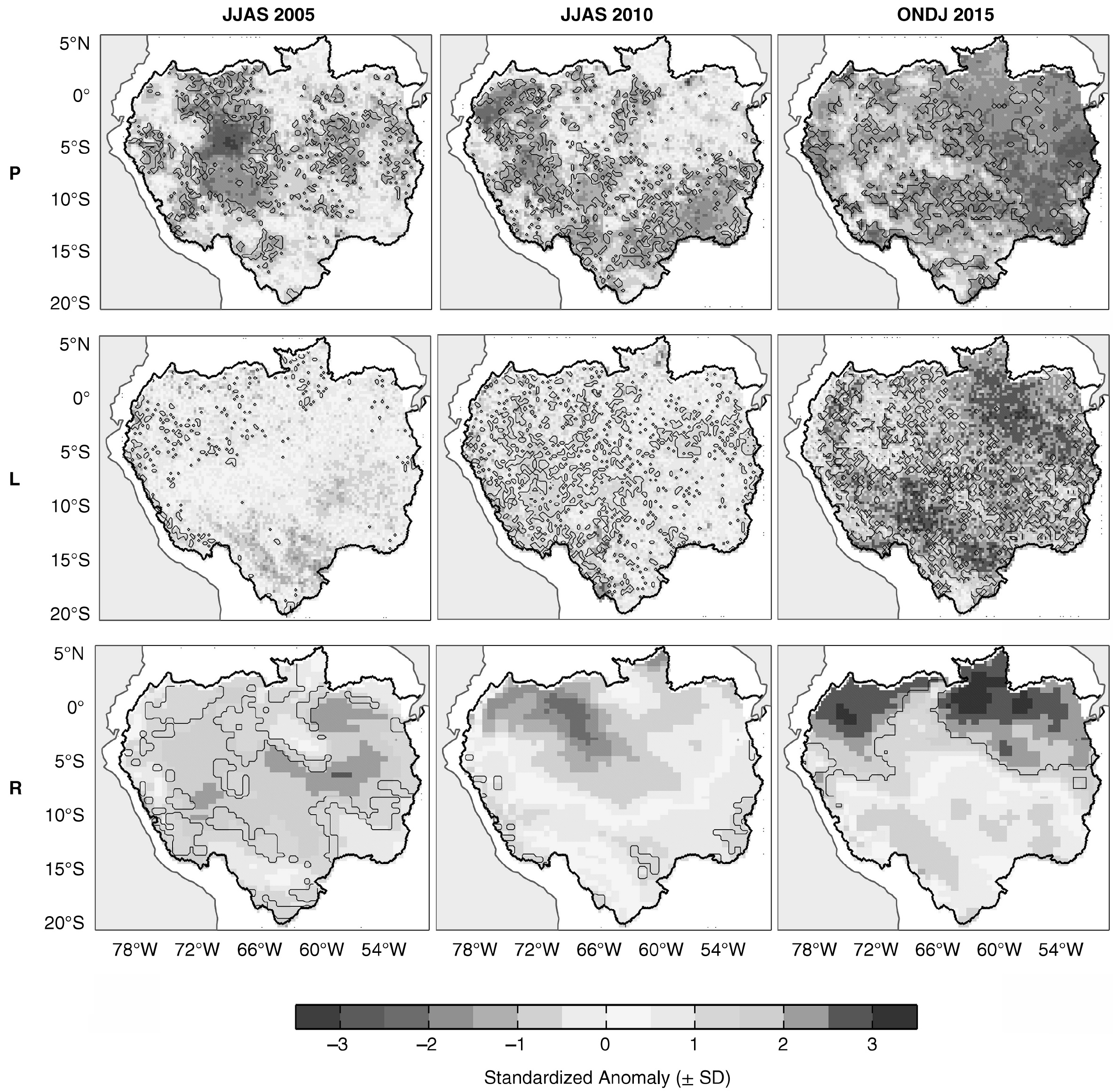

Figure 1. Spatial patterns of standardized anomalies of precipitation (P – upper panels), LST (L – middle panels) and solar radiation (R – lower panels) relative to 2000–2015, during 2005 (JJAS – left panels), 2010 (JJAS – central panels) and 2015 (ONDJ – right panels). Record-breaking of minimum precipitation and maximum LST and solar radiation values for the 15-year period are demarked by contour lines. [Colour figure can be viewed at wileyonlinelibrary.com].

The area stricken by precipitation deficits has increased over the years, rising from 37.9% in 2005 to 42.9% in 2010 and almost doubling in 2015 with 80.1% of the Basin affected. The impact of such observed growth may be associated nor only to the total area stricken, but also with the accumulated effect of the consecutive droughts (Davidson *et al.,* 2012). In addition to rainfall, the most prominent meteorological variable during 2010 and 2015 was temperature and although it showed minimal influence in 2005, it was connected with observed negative temperature anomalies in JJAS (Figure 1). These anomalies may be associated with cold front intrusions, which are more frequent during the austral winter (Li and Fu, 2006; de Neto *et al.,* 2015). Although biomass burning aerosols and anomalously late dry-seasons may block cold front incursions from extra-tropical South America into southern Amazonia (Zhang *et al.,* 2009; Fu *et al.,* 2013), a large number of cold air intrusions episodes were reported by the monthly *Climanalise* bulletins of the Center for Weather Forecast and Climate Studies (CPTEC) in the austral winter of 2005, leading to a large decline in the temperature. The area affected by high temperature values has also increased over the years (Table 2). The area disturbed by drought in 2015 was at a maximum in ONDJ (90%), but although ENSO's influence on Amazon rainfall is limited to the wet season (Yoon and Zeng, 2010), our results showed that it significantly influenced temperature in JJAS (83%). For 2005 and 2010, the area stricken by high temperature

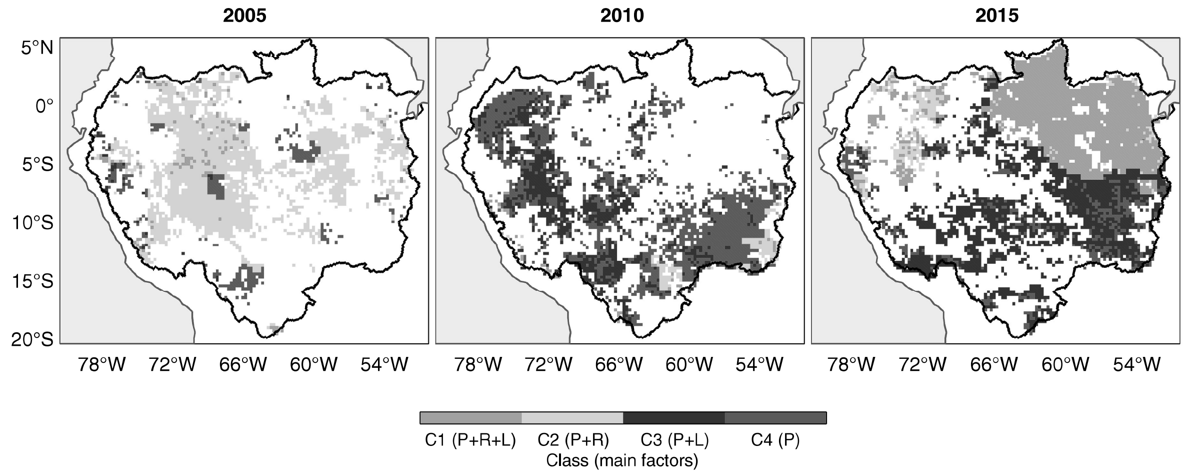

Figure 2. Spatial patterns of classes C1 (P + R + L), C2 (P + R), C3 (P + L) and C4 (P) over the Amazon Basin during the drought events of 2005 (left panel), 2010 (central panel) and 2015 (right panel). Each class corresponds to the concurrent combination of the minimum signal of precipitation (P), and maximum signals of LST (L) and solar radiation (R), during the 15-years period (2000–2015). [Colour figure can be viewed at wileyonlinelibrary.com].

values peaked in FMAM, covering respectively, 19.5% and 59.6% of AB, instead of JJAS when 10.3% and 42% of the basin was warmer than normal. This suggests a possible role for the cold intrusions in the timing of the temperature anomalies. These intrusions increase the temperature variability in JJAS and the positive temperature anomalies induced by droughts linked to TNA warming may be not capable of overcoming the natural variability during JJAS.

The spatial pattern of LST was, in general, consistent with the spatial pattern of precipitation anomaly, shown by the negative correlation observed between these variables, i.e., precipitation deficits are usually associated with positive LST anomalies (Figure 1, top and middle panels). The spatial pattern of LST showed the unusual warmth that affected the entire AB in 2015, when the standardized anomalies were particularly pronounced, exceeding the 2000–2015 mean by more than +3 SD and possibly being likely warmest on record for that 15 year period. Our results align with the NASA's Goddard Institute for Space Studies (GISS) analysis that showed October to December of 2015 as the warmest months on record, highlighting the impact of the 2015–2016 El Niño on surface temperature (Hansen *et al.,* 2010; GISTEMP Team, 2017). It should be noted that during the previous drought event of 2010, the region also experienced extreme LST anomalies that broke the JJAS records, mainly in the western sector of the AB. Marengo *et al.* (2011) have reported that during March to August 2010 the TNA-SST were the highest since 1923 and led to an extreme drought event during the dry season. These changes in precipitation together with high surface temperatures, which allow high evaporation rates, strongly impacted the river levels. At that time, 2010 was considered the warmest year ever recorded and this record-breaking was remarkable as the second half of the year was characterized by a transition to an intense La Niña event (Hansen *et al.,* 2010; Espinoza *et al.,* 2011; Marengo *et al.,* 2011; Marengo and Espinoza, 2016; GISTEMP Team, 2017).

The area affected by anomalous values of solar radiation showed maximums during the same 4-month periods of minimum precipitation for all years, evidencing, as expected, a high correlation between these two variables (Table 2). However, the spatial patterns of solar radiation (Figure 1, bottom panel) observed during the three drought years presented marked differences. The amount of solar radiation reaching the surface is related to the movement of the ITCZ that reaches its northernmost position early in austral winter and southernmost during austral summer (Wang and Fu, 2007; Yoon and Zeng, 2010). Espinoza *et al.* (2011) and Marengo *et al.* (2011) showed that the warming in the TNA-SST forced an anomalous northward displacement of the ITCZ in 2005 and 2010. A surplus of solar radiation was observed in the entire AB in 2005, particularly in the central region, with 78.4% of the area being affected by anomalous positive values. Decreased cloudiness was reported as the cause of the greater availability of sunlight during 2005 (Huete *et al.,* 2006; Saleska *et al.,* 2007; Bi *et al.,* 2015). In contrast, during 2010, negative anomalies were observed in the north, with positive anomalies found in the south. Such negative anomalies may be explained by a strong La Niña episode that started in May 2010 and prevailed during the second half of 2010 increasing convection and hence cloudiness in northern Amazonia (Marengo, 1992; Yoon, 2016). During 2015, near-normal solar radiation conditions were observed in the centre and south, with positive anomalies found in the north. It should be noted that record-breaking solar radiation surpluses were observed in north-eastern AB in 2015, exceeding the 2000–2015 mean by more than +3.5 SD, being in agreement with El Niño–induced droughts when their impacts are normally stronger just in the north-eastern sector.

Table 3. Fraction (%) of the Amazon Basin area affected by each class C1 (P + R + L), C2 (P + R), C3 (P + L) and C4 (P) for the considered drought event.

Classes	Drought events		
	2005	2010	2015
C1	1.7%	0.8%	**22.8%**
C2	**26.2%**	1.9%	4.1%
C3	0.5%	**12.7%**	**21.6%**
C4	4.3%	**22.3%**	6.8%

Bold values correspond to the pairs of classes/drought events that affected more than 10% of the AB.

The distinctive impact of each meteorological variable during the three drought events, as obtained by the four defined classes (Table 1) is summarized in Figure 2. From Figure 1 and Table 2 the strong effect of precipitation and solar radiation in 2005 over the western and southwestern part of the AB is evident, whereas negative temperature anomalies are observed in the south and southeast. Accordingly, the 2005 episode was dominated by class C2 affecting 26.2% of the Basin (Table 3), mainly over the west and southwest (green spot in Figure 2), which means that this event was controlled by the simultaneous occurrence of a precipitation minimum and solar radiation maximum. In contrast to 2005, solar radiation had a lower impact in 2010, whereas both precipitation and temperature had strong effects with it being one of the warmest years on record. Consequently, both class C3 (minimum P and maximum L) and class C4 (minimum P) had significant roles in the 2010 event, with 12.7 and 22.3%, respectively, of the entire Basin exhibiting extreme values. The spatial patterns of class C2 in 2005 and classes C3 and C4 in 2010 were very similar, with exception of south-eastern Amazonia in 2010, a region typically affected by El Niño events and covered by class C4 (Grimm, 2003; Yoon and Zeng, 2010). Contrasting with the other events, the main classes of 2015 were C1 (minimum P and maximum L and R) and C3 (minimum P and maximum L) with 22.8 and 21.6%, respectively, of the entire AB showing extreme values, revealing the important role of temperature in 2015. The location of the class C1 in 2015 was restricted to the north-eastern sector, an area not affected in 2005 and 2010, which is consistent with the area typically impacted during El Niño events, and the class C3 is mainly concentrated in the south-eastern sector of the AB (Figures 2 and 3). Within the analysed droughts episodes, only the 2015

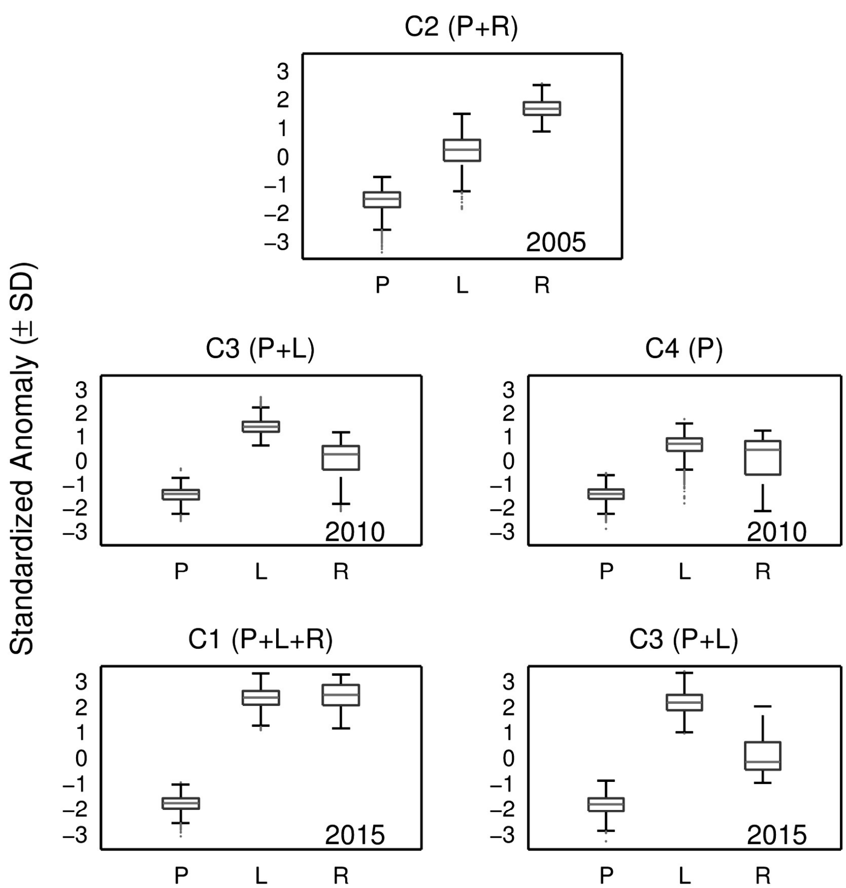

Figure 3. Boxplots of standardized anomalies of precipitation (P), LST (L) and solar radiation (R) for the pairs of classes/drought events highlighted in Table 3, namely C2/2005 (upper panel), C3/2010 and C4/2010 (middle panel) and C1/2015 and C3/2015 (lower panel). [Colour figure can be viewed at wileyonlinelibrary.com].

episode, linked to the intense El Niño of 2015–2016, had joint drivers of precipitation, temperature and radiation.

Figure 3 shows boxplots of standardized anomalies of precipitation, LST and solar radiation for the main classes presented in AB during the three drought episodes. Precipitation standardized anomalies were negative, ranging between −1 SD and −2 SD, being lowest in the case of 2015 and alike in the other two events. In 2015, class C1 showed the highest solar radiation anomalies, with the high values of radiation anomalies over class C2 in 2005 also being notable. LST anomalies were higher in 2015 (both classes) than in 2010 but were near to zero in 2005. An interesting and contrasting feature was observed for class C3 in 2010 and 2015; precipitation (LST) anomalies were lower in 2015 and higher in 2010 whereas radiation anomalies were close to 0. This seems to indicate that the observed conditions in terms of precipitation, LST and radiation over class C3 were more extreme in 2015 than in 2010. Moreover, class C1, during 2015, was characterized by the most extreme conditions of all the considered variables: lowest values of precipitation and highest values of LST and solar radiation.

4. Conclusions

The analysed extreme drought episodes were dominated by different circulation regimes, and consequently, our results highlighted that they varied markedly in terms of temporal intensity and spatial patterns. Warming TNA-SST associated droughts, such as the event of 2005, affect mainly the western AB during the austral winter, whereas El Niño-associated ones (e.g. 2015) have prominent consequences in the eastern portion during the austral summer. The particular case of 2010, which was associated with the consecutive occurrence of an El Niño and a strong warming of the TNA-SST, showed impacts on both the southwestern and south-eastern AB during austral winter. Additionally, the area stricken by precipitation deficits almost doubled from 2005 to 2015, reinforcing the widespread character of El Niño-associated droughts.

Briefly, the exceptional character of the 2015 drought episode could be related to (i) the extremely high precipitation deficit that was observed in ONDJ, (ii) the fact that 80% of the AB was stricken by a precipitation deficit, the eastern portion in particular; (iii) the effects of solar radiation and LST, the latter being extreme for approximately 90% of the basin; (iv) the joint role played by the three variables, exhibiting record-breaking values for precipitation (LST and solar radiation) that exceed the 2000–2015 average by less (more) than −2.5 SD (+3.0 SD and +3.5 SD).

Despite the identification of climate anomalies in precipitation, solar radiation and LST, impacts remain to be investigated. The widespread characteristics of the 2015 drought, when compared to the 2005 and 2010 events, suggests huge consequences to ecosystems and the local people. During the drought years, despite drought spatial variability, intense tree mortality was observed, potentially changing the role of Amazon from that of a carbon sink to being a carbon source to the atmosphere (Phillips *et al.,* 2009; Lewis *et al.,* 2011; Anderegg *et al.,* 2013). It should be stressed that most of the region consists of closed-canopy broadleaf evergreen forest, gradating to savanna in the south-eastern portion, where deforestation and fire practices are prominent (Aragão *et al.,* 2007). Furthermore, the increased frequency and intensity of droughts over the AB may also be related to increased atmospheric aerosol concentrations which promote feedbacks mechanisms between deforestation, fire and drought (Cox *et al.,* 2008; Bevan *et al.,* 2009). Recent results highlighted the characteristic time-scales at which vegetation from different biomes respond to drought. Although there is low influence of drought on vegetation in humid biomes, due to the positive water balance along with low water efficiency demonstrated by vegetation in these regions, in 2005 and 2010 the vegetation of the AB experienced significantly low net primary production (Vicente-Serrano *et al.,* 2013). This effects disturbed the biotic integrity, compromising ecosystem services and disturbing the social-economic resilience which in turn increased the vulnerability of the local populations (Pinho *et al.,* 2015).

Global circulation models project an increase in both frequency and intensity of droughts in the AB (Cox *et al.,* 2008; Guimberteau *et al.,* 2013; Duffy *et al.,* 2015), primarily due to (i) the increase of SST over the Pacific and consequently El Niño events (Meehl *et al.,* 2007) and (ii) the increase of TNA-SST and a shift in the northwest direction of the ITCZ (Marengo *et al.,* 2008). In this context of climate change, the frequency of the extreme drought episodes in the AB during the last 15 years, one episode every 5 years with a significant increase in the coverage area, is remarkable and reinforces the concern regarding changes in this ecosystem's dynamics and its ability to capture carbon (Aragão *et al.,* 2007; Brienen *et al.,* 2015; Feldpausch *et al.,* 2016).

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