Two Contrasting Severe Seasonal Extremes in Tropical South America in 2012: Flood in Amazonia and Drought in Northeast Brazil

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ABSTRACT

Two simultaneous extreme events affected tropical South America to the east of the Andes during the austral summer and fall of 2012: a severe drought in Northeast Brazil and intense rainfall and floods in Amazonia, both considered records for the last 50 years. Changes in atmospheric circulation and rainfall were consistent with the notion of an active role of colder-than-normal surface waters in the equatorial Pacific, with above-normal upward motion and rainfall in western Amazonia and increased subsidence over Northeast Brazil. Atmospheric circulation and soil moisture anomalies in the region contributed to an intensified transport of Atlantic moisture into the western part of Amazonia then turning southward to the southern Amazonia region, where the Chaco low was intensified. This was favored by the intensification of subtropical high pressure over the region, associated with an anomalously intense and northward-displaced Atlantic high over a relatively colder subtropical South Atlantic Ocean. This pattern observed in 2012 was not found during other wet years in Amazonia such as 1989, 1999, and 2009. This suggests La Niña as the main cause of the abundant rainfall in western Amazonia from October to December, with wet conditions starting earlier and remaining until March 2012, mostly in northwestern Amazonia. The anomalously high river levels during the following May–July were a consequence of this early and abundant rainy season during the previous summer. In Northeast Brazil, dry conditions started to appear in December 2011 in the northern sector and then extended to the entire region by the peak of the rainy season of February–May 2012.

1. Introduction

The year 2012 featured two simultaneous ‘‘once in a century’’ extreme seasonal events in tropical South America: intense rainfall in Amazonia (AMZ) that generated the record flooding there and the extreme drought that affected Northeast Brazil (NEB). The flooding in 2012 surpassed the previous record in 2009, and the drought in Northeast Brazil was even more intense than the previous record drought during El Niño 1998. Droughts and floods are part of the natural climate variability in those regions and have occurred in the past. However, what calls attention in 2012 is the synchronicity of these two contrasting extreme events, something that has not been observed with such intensity in the recent recorded climate history of the area.

In Amazonia and Northeast Brazil, the rainfall exhibits marked interannual variability, part of which has been attributed to the sea surface temperature (SST) variations in the tropical Pacific manifested as the extremes of El Niño–Southern Oscillation (ENSO) and to the

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meridional SST gradient in the tropical Atlantic (Kousky et al. 1984; Aceituno 1988; Ropelewski and Halpert 1987, 1989; Kousky and Ropelewski 1989; Marengo and Hastenrath 1993; Hastenrath and Greischar 1993; Uvo et al. 1998; Ronchail et al. 2002; Yoon and Zeng 2010; Marengo et al. 2008a,b, 2011, 2012; Andreoli et al. 2011; Kayano et al. 1988; Coelho et al. 2002, 2012; Souza and Ambrizzi 2002; among others). In physical terms, precipitation anomalies over those regions are controlled by changes in the zonally oriented Walker circulation due to changes in SST anomalies in the equatorial Pacific Ocean, though El Niño explains only part of the variability (Ronchail et al. 2002; Rao et al. 1996; Marengo et al. 2001; Marengo 1992; Yoon and Zeng 2010).

The flooding in Amazonia and drought in Northeast Brazil in 2012 occurred when a La Niña event was present in the tropical Pacific during austral summer and with the tropical Atlantic relatively neutral, without important SST anomalies during austral summer and fall (www.cptec.inpe.br). Situations like this have not been detected in the recent past. An opposite situation occurred during El Niño 1925/26, with warm temperatures persisting in the tropical Pacific starting May 1925 and lasting for 16 months. While a severe drought affected Amazonia in 1925/26 (Williams et al. 2005), Northeast Brazil was wet at this time when normally an El Niño would bring dry conditions.

Droughts and floods manifest themselves with varying intensity, caused by: deficient or excessive rainfall, late or early onsets of the rainy seasons, or high air temperatures and low humidity for droughts. In the present case in Northeast Brazil, there was a pronounced rainfall deficit below the minimum required by the plantations during austral summer and fall. On the other hand, in the Amazonia region, the floods were detected more as record high levels in various rivers in the region during the austral fall and winter season, as a consequence of increased rainfall during the previous summer season.

The present study focuses on the observed large-scale atmospheric characteristics in the Amazonia and Northeast Brazil regions during the austral summer and fall seasons of 2012, which resulted in the most extensive flooding episode in Amazonia—and the most extreme drought in Northeast Brazil in recent hydroclimatic history. We use a combination of global reanalyses and sea surface temperature in the tropical Pacific and Atlantic to identify the large-scale circulation features from austral spring to fall. Two rainfall datasets from observations, satellite-derived products, and river data from the Amazonia region were used to verify the coherence of rainfall anomaly patterns and extreme river flow discharges, as well as rainfall anomalies in Northeast Brazil.

2. Climate and hydrology features in tropical South America to the east of the Andes during summer and fall 2012

a. Amazonia region

According to Brazilian newspapers and various government monitoring agencies, the Amazonia region experienced one of the worst flooding episodes in history, with most of the state of Amazonas (52 of the 62 districts) under a state of emergency as the Solimões River and the Rio Negro—the two main branches of the Amazon River—overflowed. The Brazilian Geological Survey [Companhia de Pesquisa de Recursos Minerais (CPRM); www.cprm.gov.br] informed the public of early rains in western and central Amazonia in the summer of 2012, which determined early peak flows of the Acre River, later affecting the levels of the Solimões and Amazon Rivers. Besides risks to life and property for nearby residents, floods also affect fishery activities and domestic agriculture (Sena et al. 2012; Vale et al. 2011; Marengo et al. 2012).

In Peruvian Amazonia, the levels of the Amazon River in Iquitos were well above normal (between 20% and 100%) due to intense rainfall between December 2011 and March 2012 that elevated the levels of its tributaries, particularly the Marañon River, and according to the National Service of Meteorology and Hydrology of Peru [Servicio Nacional de Meteorología e Hidrología del Perù (SENAMHI); www.senamhi.gob.pe], the Marañon River contributed about 60% to the variability of levels at Iquitos and the other tributary, the Ucayali River, contributed 40%. In Iquitos, the emergency level, considered to be 117 m above mean sea level (MSL), was surpassed in March 2012, with waters reaching a record high of 118.97 m MSL. In Tamshiyacu (about 45 km south of Iquitos), a discharge of 55 125 $m^3 s^{-1}$, the highest since 1983, was detected on 19 April 2012. In Leticia, in the Colombian Amazonia, the level of the Amazon River was also well above normal, surpassing the critical level of 70.20 m MSL in April 2012, according to the Institute of Hydrology, Meteorology, and Environmental Studies [Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM); www.ideam.gov.co].

Amazonia is continually subject to floods as part of its natural climate variability. During the seven years ending 2012, severe floods were detected in western and central Amazonia in 2009, 2011, and now in 2012. Previous observational studies (Marengo 2004; Ronchail et al. 2002; Marengo et al. 2008a,b, 2011, 2012; Tomasella et al. 2011; Espinoza et al. 2011, 2012, 2013; Yoon and Zeng 2010) have identified deficiencies or excesses of rainfall that have produced droughts and floods in Amazonia associated with ENSO, with strong warming in the tropical Atlantic, or a combination of both. Previous floods in Amazonia in 1953/54 and 2008/09 were related to a warm tropical South Atlantic in the absence of La Niña, while floods in 1988/89 and 1998/99 occurred during La Niña (Marengo et al. 2012). Of 12 Rio Negro flood events recorded at Manaus since 1903, 8 occurred during La Niña episodes (Kane 2001).

During what was called at the time the "flood of the century" in 2009 (Marengo et al. 2011), the levels of the Rio Negro at the Manaus harbor during July 2009 reached a then record high of 29.77 m MSL, according to CPRM. The six previous record highs observed in Manaus and their return periods [RP; calculated following Chow et al. (1988)] were 1953 (29.69 m MSL; RP = 37 yr), 1976 (29.61 m MSL; RP = 28 yr), 1989 (29.42 m MSL; RP = 22 yr), 1922 (29.35 m MSL; RP = 18 yr), and 1999 (29.30 m MSL; RP = 16 yr), and the other records observed in Manaus were 1909 (29.17 m MSL; RP = 14 yr), 1971 (29.12 m MSL; RP = 12 yr), 1975 (29.11 m MSL; RP = 11 yr), and 1994 (29.05 m MSL; RP = 10 yr; CPRM 2009). The level of the Rio Negro reached 29.97 m MSL on May 2012, with an RP of 110 yr (the highest mark since 1903), while the water level in 2009 represented an RP of about 55 yr. It is important to note that the water level at this station is controlled by the Solimões, through backwater effects (e.g., Meade et al. 1991; Filizola et al. 2009).

b. *Northeast Brazil*

Several studies have indicated that most of Northeast Brazil tends to receive more precipitation during La Niña episodes, but the year 2012 did not follow that pattern. During La Niña 2012, the same year as the floods in Amazonia, Northeast Brazil declared a state of emergency in most districts in the region due to a drought considered to be the most severe in the last 30 years, affecting more than 4 million people. According to local newspapers, from January to May 2012 the drought in 2012 had already destroyed large swaths of cropland, causing drinking water shortages in hundreds of cities and towns across the region and leaving ranchers struggling to feed and water cattle.

Droughts have been reported in Northeast Brazil since the sixteenth century (Magalhães et al. 1988). The last extreme drought, in 1998, (due to El Niño/warm tropical North Atlantic) stretched across most of the region, seriously affecting crop production in the area and threatening the local food supply. The 2012 severe drought that gripped the northeast took its toll on more than 1100 towns, even triggering fighting in rural areas for water allocation. Unofficial estimates from the Brazilian Ministry of Integration estimated that losses to the agricultural sector of the order of USD 6 billion could be expected.

The history of drought in Northeast Brazil, as collected from various sources (Moura and Shukla 1981; Araujo 1982; Magalhães et al. 1988; Aceituno et al. 2009) was updated in this study to include 2012. Of the 45 droughts on record since the sixteenth century, only two (1907 and 2012) occurred during La Niña years. According to the Australian Bureau of Meteorology (www.bom.gov.au), the 1906/07 La Niña was considered as weak–moderate while the La Niña in 2012 was classified as strong; however, 1907 was not a wet year in Amazonia.

Previous droughts in Northeast Brazil have had the following impacts: in 1777–80, almost 85% of livestock and half of the population died because of famine; in 1877–79, almost 200 000 people died in the city of Fortaleza (capital of the state of Ceará) because of famine and as a consequence of diseases brought by the migrants; the drought in 1907 affected mostly the states or Ceará and Rio Grande do Norte in northern Northeast Brazil; in 1915, more than 278 000 people died in the state of Ceará and about 75 000 people migrated to other regions; in 1979–81, there was a greater than 70% reduction in the production of rice, beans, and cotton and prices went up by about 100%; in 1958, an estimated 10 million people fled from Northeast Brazil as a result of drought (Namias 1972; Hastenrath and Heller 1977); in 1982/83, there was a loss of 80% of livestock; and in 1998, 57% of the total agricultural production of the region was lost, and the economic damages were estimated to be 5% of the gross domestic product (GDP) of the entire region.

Since the 1950s, the government started taking action against droughts including the building of reservoirs and channels and social programs for affected people, and since the 1970s no more deaths due to drought were registered, even though the exodus from the semiarid region during droughts still continues. Of the droughts of 1992, 1998, 2002, 2010, and 2012, only those of 1998 and 2002 occurred during El Niño years.

3. Objectives

The objectives of this study are to explore the main observed climatic and hydrological characteristics of the Amazonian floods and the drought in Northeast Brazil in 2012 and can be summarized as

- an assessment of regionwide meteorological and hydrological characteristics during the severe drought in Northeast Brazil and flooding in Amazonia in the hydrological year from October 2011 to July 2012,

using a combination of river data and various rainfall datasets;
- an assessment of the large-scale circulation fields from the early austral summer to the autumn 2012, focusing on circulation anomalies in the tropical region of South America during these two extreme simultaneous events; and
- an assessment of past occurrences of these concurrent events and investigation into possible long-term trends.

4. Data and methodology

Rainfall estimates from the satellite-based Tropical Rainfall Measurement Mission (TRMM) are used for assessments of monthly rainfall anomalies. Although this product overestimates light rainfall and underestimates heavy rainfall (Aragão et al. 2007) and precipitation over mountainous areas (Lavado et al. 2009; Condom et al. 2011), it has been frequently used for large-scale climatic studies over the Amazon basin (Saleska et al. 2007; Philipps et al. 2009; Lewis et al. 2011) and shows consistency with gridded and station-based datasets. The TRMM data used in this article (Rozante et al. 2010) represent a combination of rain gauge datasets from the global telecommunication systems (GTS), automatic stations from various agencies in South American countries, and the real-time TRMM precipitation 3B42RT product, which shows higher-quality gridded datasets, with 0.25° spatial resolution. Anomalies are calculated in relation to the 1998–2010 long-term mean (LTM).

In addition, we used monthly precipitation from the Global Precipitation Climatology Centre (GPCC) full data product, version 4, updated December 2011. The GPCC is a global gauge-based monthly precipitation dataset for land, available on a 1.0° × 1.0° latitude/longitude grid. The dataset used covers the period 1951–2012 and is based on both non-real-time and real-time stations. The GPCC dataset has been useful in complementing the information provided by rain gauge observations and has been used in previous studies over Amazonia (e.g., Marengo et al. 2011, 2012).

We used GPCC monthly rainfall data from 1961 to 2012. The February–May (FMAM) season is defined as the peak season for rainfall anomalies both in Amazonia and Northeast Brazil. Both regions are the driest in August and wettest in FMAM, with the rains beginning in October–November in Amazonia and November–December in Northeast Brazil. Anomalies were calculated from the 1961–90 mean for areas representing central-western Amazonia (2°N–8°S, 57°–74°W) and Northeast Brazil (5°–10°S, 38°–45°W).

Circulation fields were extracted from the National Centers for Environmental Prediction (NCEP) global reanalyses (Kalnay et al. 1996) on a 2.5° latitude/longitude grid and are available from 1948 to the present. The observed SST was provided by the Met Office Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) data, available from January 1903 to the present (D. E. Parker et al. 1995, unpublished manuscript). The anomalies were calculated from the maximum length of each dataset for the Niño-3.4 region (5°S–5°N, 170°–120°W) in the tropical Pacific during austral summer [December–February (DJF)]. Over the tropical Atlantic we used the regions defined by Marengo et al. (2008a), the tropical North Atlantic (12°–27°N, 20°–50°W) and tropical South Atlantic (0°–15°S, 0°–15°W), to calculate the index of the tropical meridional SST gradient. Vertically integrated moisture transport from the surface to 500 hPa was calculated following Satyamurty et al. (2013).

Main stem river discharge and level data from gauge sites in Amazonia were provided by the Brazilian Water Agency [Agência Nacional de Águas (ANA)] and SENAMHI. To characterize the long-term level/discharge variability of the Amazonia basin hydrology, station records for the Rio Negro at Manaus and for the Amazon River at Iquitos and Santa Rosa were used from the beginning of their records: 1903–2012 for Manaus, 1996–2012 for Santa Rosa, and 1969–2012 for Iquitos, and for the annual and high season May–July (MJJ) were used for Manaus and April–June (AMJ) were used for Santa Rosa and Iquitos.

5. Large-scale circulation features and rainfall anomalies from austral summer to fall in Amazonia–Northeast Brazil for 2012

a. *Circulation and SST anomalies*

In the context of large-scale circulation, rainfall in tropical South America depends on the development of intense convective activity over the region, which is determined by the confluence of the tropical Atlantic trade winds and the meridional displacements of the intertropical convergence zone (ITCZ) on both sides of the Andes. The migration of the ITCZ depends on the intensity of the northeast and southeast trades that is associated with the meridional gradient of sea level pressure (SLP) and SST in the tropical North and South Atlantic (Hastenrath and Heller 1977). In addition, upper-level cyclonic anomalies over Northeast Brazil as well as SST anomalies in the tropical Pacific affect the meridional position of the ITCZ.

An episode of La Niña occurred from September 2011 to the summer of 2012 (Figs. 1a–g), with maximum

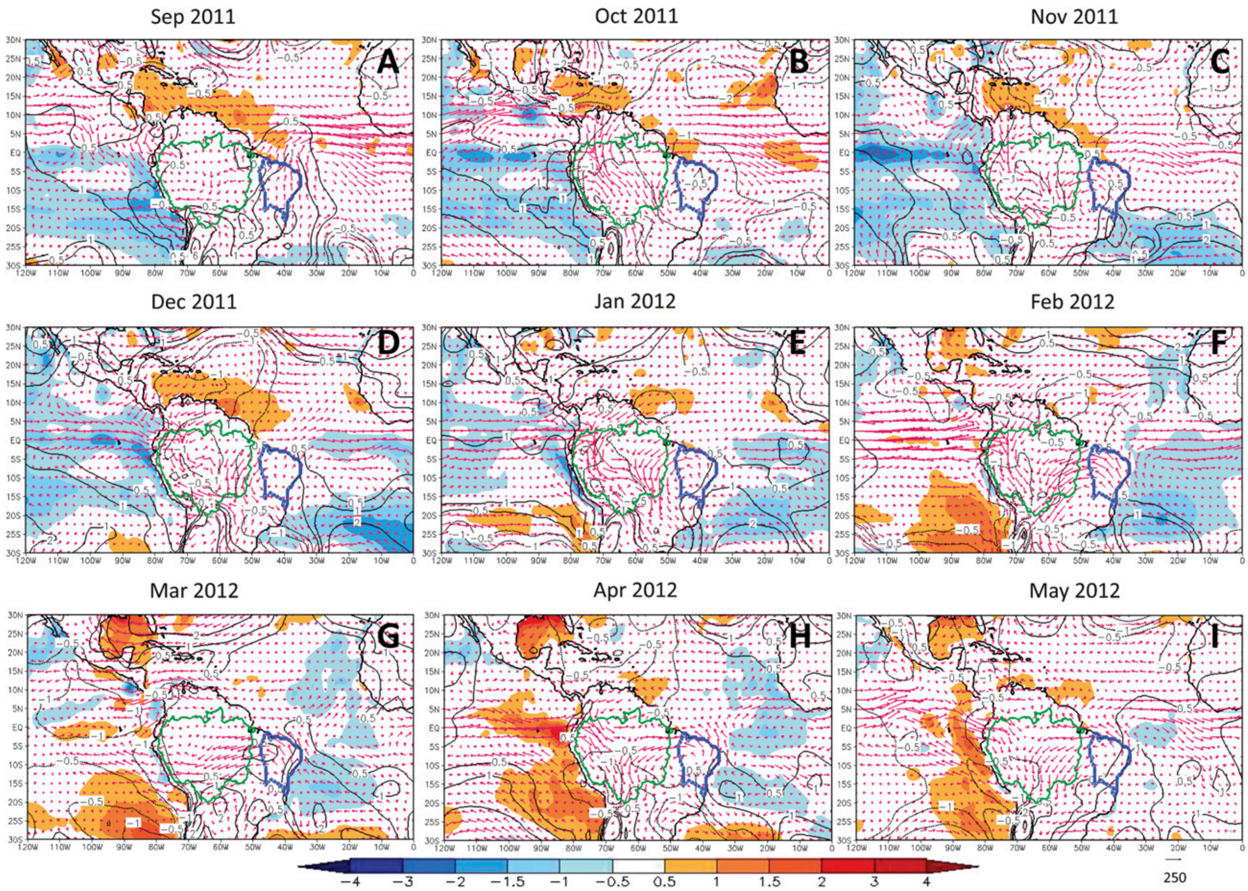

FIG. 1. Seasonal SST anomalies (°C), SLP anomalies (hPa), and anomalies of vertically integrated moisture transport from the surface to 500 hPa in South America from Sep 2011 to May 2012. SST and circulation anomalies correspond to the 1961–2012 LTM. The bar at the bottom of the panel shows the scale of the SST anomalies. The vector at the bottom rhs of the panel shows the scale of the moisture transport ($kg^{-1}\,m\,s^{-1}$). Black full lines show SLP anomalies (hPa).

intensity (cooling of 2°–3°C in the equatorial Pacific) in November 2011. At the same time, the tropical Atlantic did not experience any significant warming off the coast of Northeast Brazil, but there was some cooling of the subtropical South Atlantic (less than 1.5°C) during early summer, and by fall the cool area moved to the tropical South Atlantic between 5° and 15°S. As described in Espinoza et al. (2013), a low-level geopotential height wave train pattern emanating from the western Pacific was identified, with positive anomalies over the subtropical South Pacific and Atlantic and negative anomalies over southeastern South America during austral summer. These patterns contribute to an intensified atmospheric flow of Atlantic moisture in the western part of Amazonia and turning southward to southern Amazonia, where the Chaco low was intensified.

Perhaps the most important feature in Fig. 1 was the behavior of the subtropical South Atlantic high during austral fall, which was intensified (by about 2 hPa) and anomalously located to the north, reaching eastern Northeast Brazil during early austral summer (October 2011–January 2011) and then during fall (March–May 2012). In fact, SLP anomalies were about +0.5 hPa during September 2011 and again from March to May 2012, which corresponds to the peak rainy season in Northeast Brazil. In Amazonia, SLP showed negative anomalies (between −0.5 and −1 hPa) in central and southern Amazonia during summer and fall.

The vertically integrated moisture transport maps show consistency with the SLP anomalies in tropical South America, where the intensification of the thermal Chaco low pressure area south of the Amazon region induced strong northwesterly moisture flow from northern to southern Amazonia during most of summer and fall, particularly from October to December 2011 and in January 2012. However, no episodes of the South American low-level jet (SALLJ) to the east of the Andes were detected between October 2011 and June 2012 (following Bonner's criterion 1). The intense flow comes from two source regions of the tropical North Atlantic: off the coast of northern South America around 5°–10°N and flowing southward along the Andes, and in the easterly flow between 0° and 5°S due to a stronger South Atlantic subtropical high situated closer to South America and over anomalously colder waters in the subtropical South Atlantic. These fluxes converge over southwestern Amazonia producing positive rainfall anomalies in this region (see Fig. 5, described in greater detail below). These conditions were due to increased moisture convergence and the effect of intraseasonal oscillations from Pacific sources, which started in October 2011 during La Niña and lasted until March 2012 determining wet conditions and increased river levels months later (www.cptec.inpe.br/clima).

For Northeast Brazil, the low-level flow suggests weak northerly trades over this region during austral summer and divergence in fall, consistent with the positive SLP anomalies inhibiting rainfall. An anticyclonic anomaly is found over a region between 5° and 15°S in the South Atlantic. The strong southerly flow pushes the region with convergence along the ITCZ to the north around 5°N–5°S over eastern Amazonia and northern Northeast Brazil during the peak of the rainy season (March–May). This is consistent with positive SLP anomalies, upper-level cyclonic anomalies over Northeast Brazil, and intraseasonal oscillation in the tropical Pacific. All of these favors reduced rainfall over that region (www.cptec.inpe.br/clima). In other La Niña years with wet conditions in Amazonia (1989, 1999, and 2009), no positive SLP anomalies in the tropical and South Atlantic were detected. Dry conditions in Northeast Brazil in 1958 also showed positive SLP anomalies during the peak rainy season in the subtropical South Atlantic region, extending over eastern Northeast Brazil.

Figure 2 shows a more coherent picture of the teleconnections patterns involved all the way from the SST anomalies in both the tropical Pacific and Atlantic Oceans to regional rainfall anomalies in Amazonia and Northeast Brazil. In Fig. 2a, the scatter diagrams show that the wettest years in Amazonia that experienced record floods (including 2012) occurred during La Niña events. Considering the SST forcing in the tropical Atlantic, Fig. 2c shows that previous wet years in Amazonia (1989, 1999, and 2009) occurred when the SST dipole was negative (tropical South Atlantic was warmer than the tropical North Atlantic), while in 2012 SST anomalies were relatively lower in both the tropical North and South Atlantic.

In Northeast Brazil, the driest years occurred during El Niño (Figs. 2b,d), the drought in 2012 being the only case from 1961 to 2012 that occurred during La Niña. Previous dry years in the region (1983, 1993, and 1998) occurred when the SST dipole in the tropical Atlantic was negative (the entire tropical Atlantic was warmer than normal) and the large-scale circulation was dominated by El Niño–related anomalies, particularly in 1983 and 1998. In 2012, as in 1958 and 1980, the tropical Atlantic SST dipole was positive, with a slightly warmer tropical North Atlantic (as observed in Fig. 1).

An analysis of the vertical motion fields together with the near-surface circulation discussed previously can provide a better idea of the regional tridimensional circulation of the region, before and during the peak of the flooding in Amazonia and drought in Northeast Brazil in 2012. Figures 3 and 4 show monthly east–west and north–south circulation anomaly maps, based on divergence and divergent circulation, for the equatorial region 5°N–5°S and along 75°–65°W, respectively. These anomaly maps for 2012 are relative to the mean composite of La Niña years (1983/84, 1988/89, 1995/96, 1998/99, 1999/2000, 2005/06, 2007/08, and 2010/11). Divergence or convergence of moisture flux matters in maintaining anomalous rainfall, according to the moisture budget equation (Zeng 1999). The linkage between the divergent component of circulation and anomalous rainfall can be established by utilizing the meridional/zonal circulation of divergent meridional/zonal wind and the vertical motion as shown in Figs. 3 and 4.

Figure 3 shows enhanced upward motion and low-level convergence near the equator and between 15° and 20°S, consistent with the intensification of the Chaco low, and anomalously strong upper-level divergence south of the equator from October 2011 to January 2012, becoming more intense between February and March around 0°–5°S. This is consistent with positive rainfall anomalies in northwestern Amazonia.

Figure 4 shows anomalous convergence at the lower level and increased upward motion with strong upper-level divergence (intense Bolivian high) detected during October 2011–May 2012 between around 70° and 100°W over western and central Amazonia. From March to May 2012, during the peak of the rainy season in Northeast Brazil, strong upper-level convergence and downward motion and low-level divergence are detected around 30°–50°W. This is consistent with subsidence over Northeast Brazil between 20° and 45°W, with an SLP increase, reduced surface moisture flux, and reduced rainfall there (Fig. 1), especially during the peak of the rainy season February–May 2012.

In summary, Figs. 3 and 4 show an alteration of the east–west circulation, resulting in increased upward motion and rainfall over extreme western Amazonia and southern Amazonia due to an intensified Chaco low and subsidence over Northeast Brazil during summer and fall 2012. The strong zonal SLP differences between

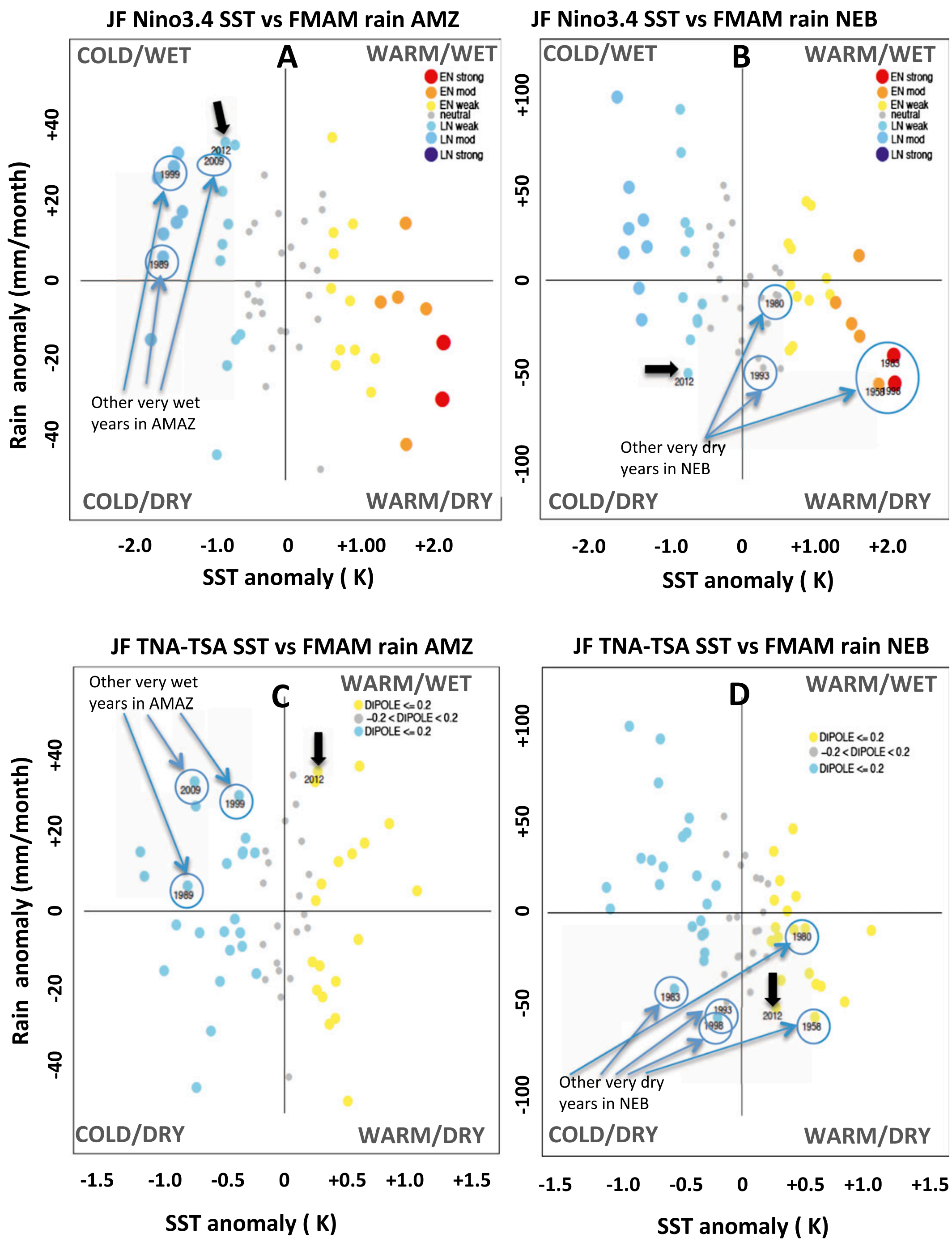

FIG. 2. Scatter diagrams of anomalies in the SST anomalies (°C) in the tropical Pacific (Niño-3.4) and the SST dipole in tropical Atlantic (SST tropical North Atlantic–SST tropical South Atlantic) during January–February and GPCC rainfall anomalies (mm month^{-1}) during the FMAM peak season in (a),(c) AMZ and (b),(d) NEB. Base period for the SST and rainfall anomalies is 1961–90. Drought years in NEB and wet years in AMZ are shown by numbers; the year 2012 is marked with an arrow and other wet years are circled.

Amazonia (low SLP anomalies) and the subtropical Atlantic (high SLP anomalies) played an important role in the near-surface circulation and convergence and rainfall anomalies during this time period.

When comparing to a composite of similar fields for La Niña events (not shown), it is noticed that during La Niña the tendency is for upward flow in tropical South America to the east of the Andes, from Amazonia to

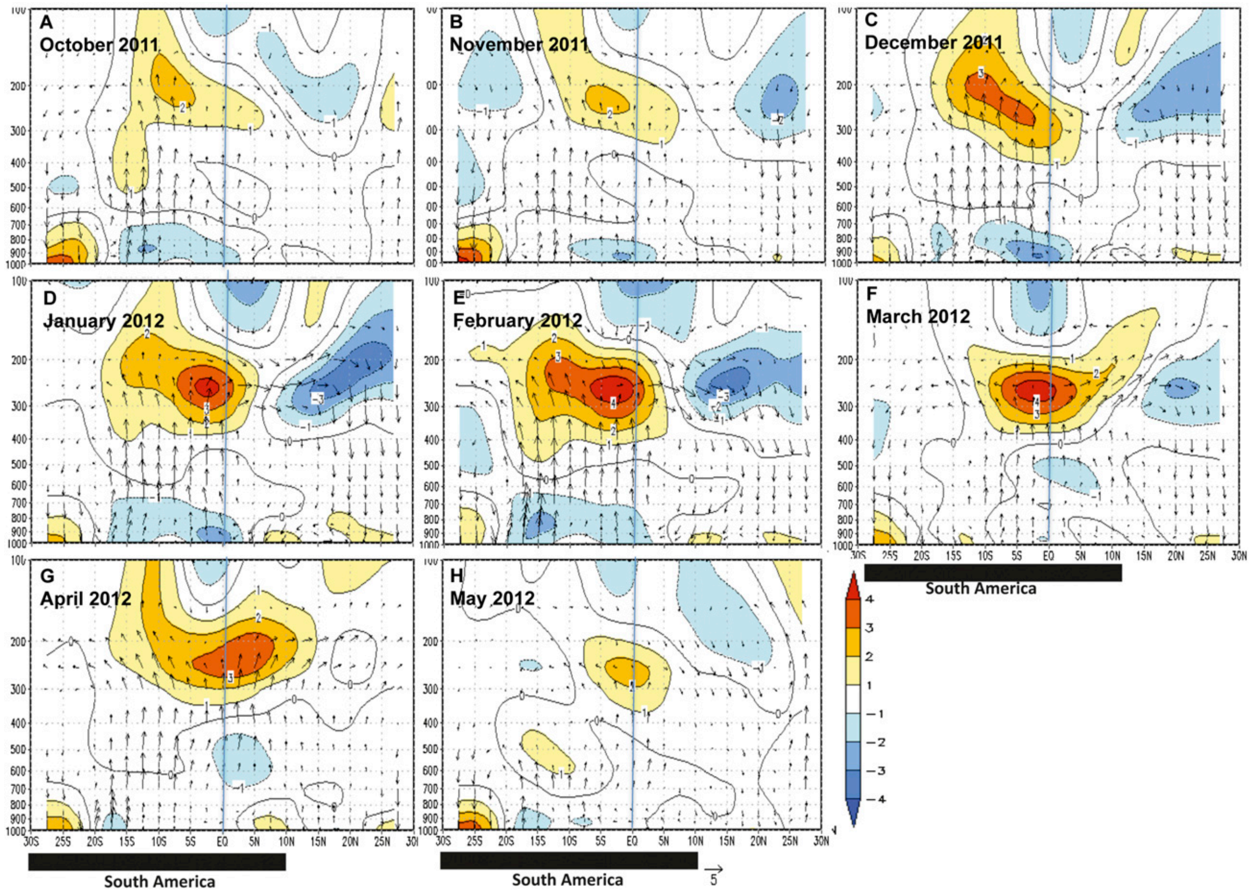

FIG. 3. Pressure–longitude section (30°N–30°S) from Oct 2011 to May 2012 of the anomalous divergence (contour interval is $1 \times 10^{-6}\,s^{-1}$) and divergent circulation averaged between 65° and 75°W. Vectors of combined pressure vertical velocity and the divergent component of the zonal wind represent the divergent circulation. Red/blue shading and solid/broken contours denote divergence/convergence anomalies. Monthly-mean departures are from a composite of La Niña events during 1981–2010 from NCEP reanalyses.

Northeast Brazil, with increased upper-level divergence from the beginning of summer. The main difference during 2012 as compared to the composite of La Niña is that the upward flow and upper-level divergence is much stronger during summer and fall over western Amazonia, and instead there was downward motion and subsidence over Northeast Brazil in summer and fall 2012.

b. *Rainfall anomalies*

According to climate reports from the Center for Weather Forecasting and Climate Studies [Centro de Previsão de Tempo e Estudos Climáticos (CPTEC); www.cptec.inpe.br/clima], rainfall in northwestern Amazonia was 200–300 mm above normal in January–March. This is confirmed by the increased terrestrial water storage found in that region since January 2012 (Espinoza et al. 2013). Meanwhile, rainfall over Northeast Brazil was about 100–200 mm below normal in January–May, during the prerainy season and the peak rainy season.

Changes in monthly rainfall derived from the TRMM products are shown in Fig. 5. In October and November, rainfall was already 4–5 mm day^{-1} above normal in western and particularly northwestern Amazonia, while rainfall was more than 3–4 mm day^{-1} above normal in the south. At the same time, Northeast Brazil rainfall was about normal. In December 2011, rainfall anomalies in western Amazonia continued to be above 3–5 mm day^{-1}, while in a region extending from eastern Amazonia to all of northern Northeast Brazil, it was 3–5 mm day^{-1} below normal. From January to May 2012, while rainfall in central and western Amazonia was between 3 and 5 mm day^{-1} above normal, in Northeast Brazil rainfall was between 3 and 4 mm day^{-1} below normal throughout the region, and the drought situation worsened in April and May 2012, particularly over northern Northeast Brazil and the coastal region of eastern Northeast Brazil (up to 5 mm day^{-1} below normal) in April and May 2012. These changes are very similar to the corresponding maps derived from GPCC, SENAMHI,

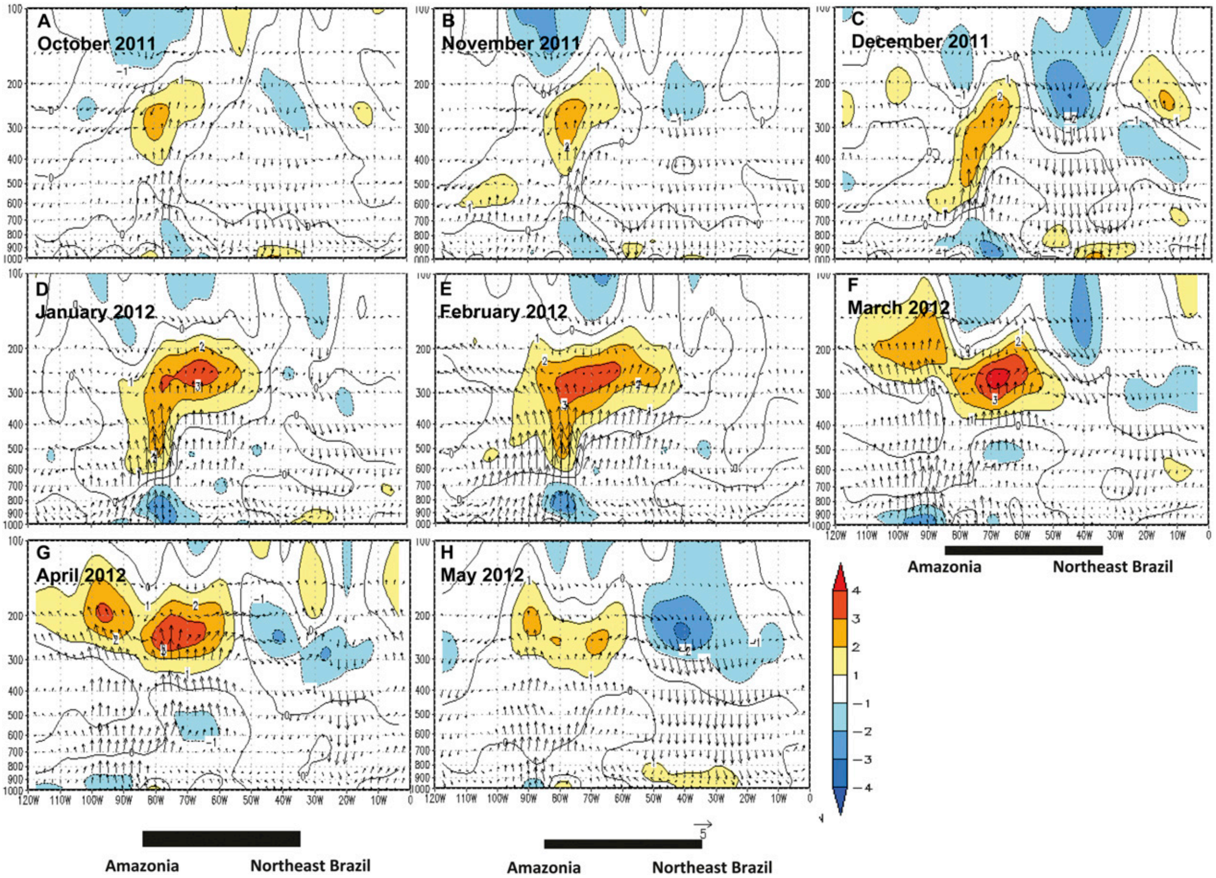

FIG. 4. As in Fig. 3, but for the average between 5°N and 5°S.

and CPTEC (not shown) and are consistent with the surface and upper-level circulation anomalies shown in Figs. 3 and 4.

The drought conditions in Northeast Brazil are related to local meteorological conditions and its influence is maximized when soil water depletion is primarily controlled by evaporation with low or absent rainfall. Estimates from NCEP reanalyses (not shown) suggest that latent heat reductions started in September 2011 and persisted until May 2011 in the semiarid region of Northeast Brazil. This is consistent with the rainfall anomaly maps (Fig. 5) from December 2011 to May 2012. Increases in sensible heat in the same region depict a pattern of less rainfall, warmer and dryer air, and increased evaporation that led to drastic soil moisture depletion during the summer and fall 2012, in agreement with the negative soil moisture anomalies from the operational analysis products from CPTEC for Northeast Brazil (http://www6.cptec.inpe.br/proclima/).

For comparison, in western Amazonia during the previous floods of 2009, rainfall was about 1–2 mm day^{-1} above normal during January–April 2009, while during the same period in 2012 rainfall was about 3–4 mm day^{-1} above normal. The extreme situation observed in 2011/12 with more rainfall in Amazonia and drought in Northeast Brazil was not detected during other wet years during the La Niña events in 1988/89 and 1998/99, where rainfall in Northeast Brazil was mainly near normal (Marengo et al. 2012).

In Amazonia, observed rainfall excesses over northwestern Amazonia in December 2011–February 2012 determined an important increase of the terrestrial water storage (TWS), as derived from the Gravity Recovery and Climate Experiment (GRACE) gravimetry from the space mission (Espinoza et al. 2013). This suggests large soil moisture recharge in that region. Soil moisture is a key parameter in the land surface–atmosphere interaction because summer precipitation over monsoon regions is sensitive to soil moisture variations (Koster 2004; Xue et al. 2006; Grimm et al. 2007; Collini et al. 2008; Saulo et al. 2010). As shown by Grimm (2003, 2004) soil water storage that develops during the wet season plays an important role in determining variations in surface air temperatures, which support regional circulation patterns.

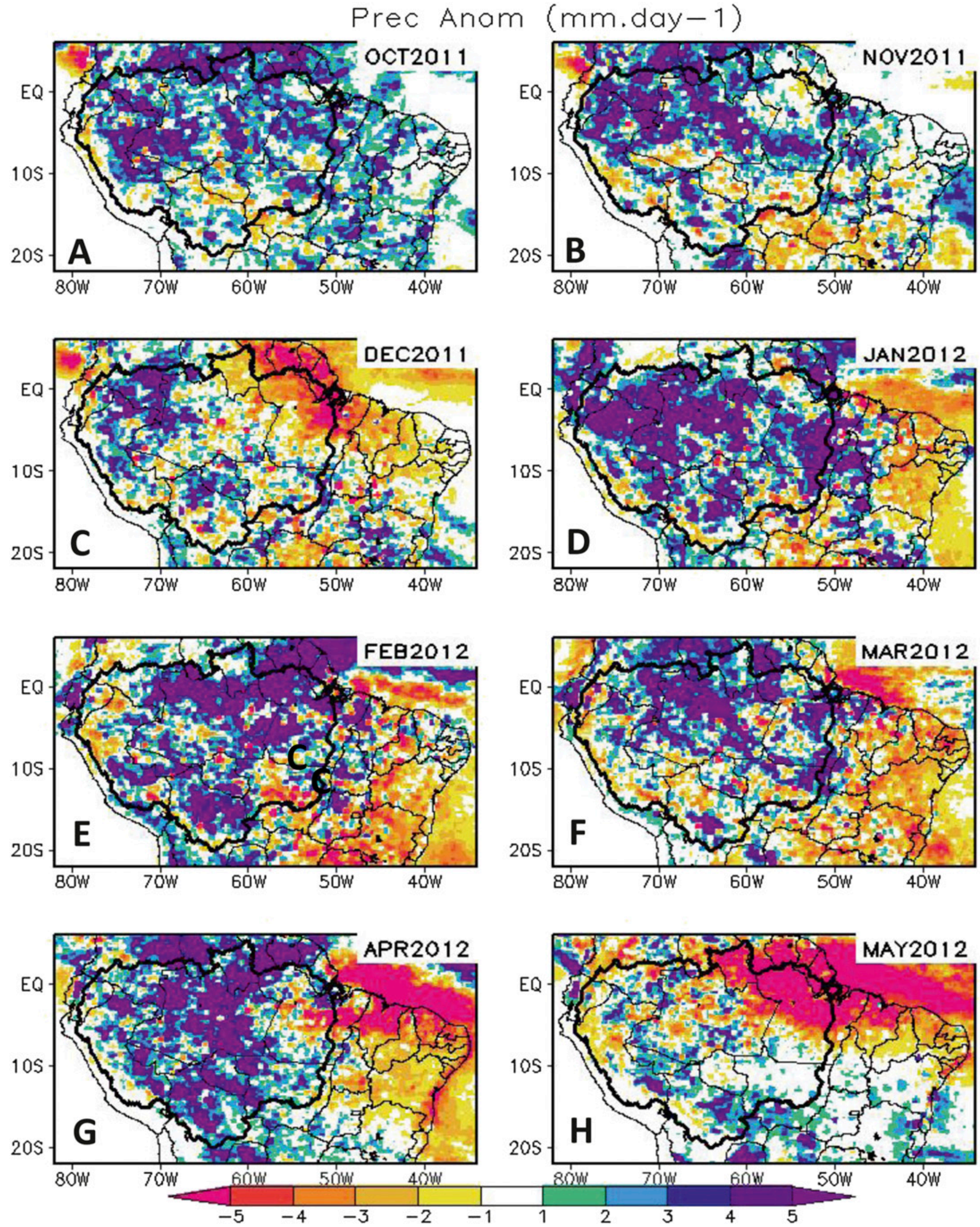

FIG. 5. Monthly rainfall anomalies (from Oct 2011 to May 2012) from the TRMM satellite estimated from the 1990–2010 climatology (mm day^{-1}). Color scale is on the lower side of the panel.

During the summer of 2012, increased soil moisture anomalies in the premonsoon seasons helped to produce circulation anomalies on the peak summer monsoon season in South America that favored conditions for excess rainfall in southern and central Amazonia, following the pattern identified by Grimm et al. (2007).

Box plots (Figs. 6a–c) provide a straightforward method of comparing the monthly precipitation observed from September 2011 to May 2012 and for the peak season FMAM 2012 in both Amazonia and Northeast Brazil during 1961–2012. The top and bottom lines on the plot represent the 85th and the 15th percentiles, respectively. The middle line in the box represents the median and the whiskers represent the minimum and maximum of all the data. The red diamonds illustrate the monthly and FMAM 2012 means of precipitation over

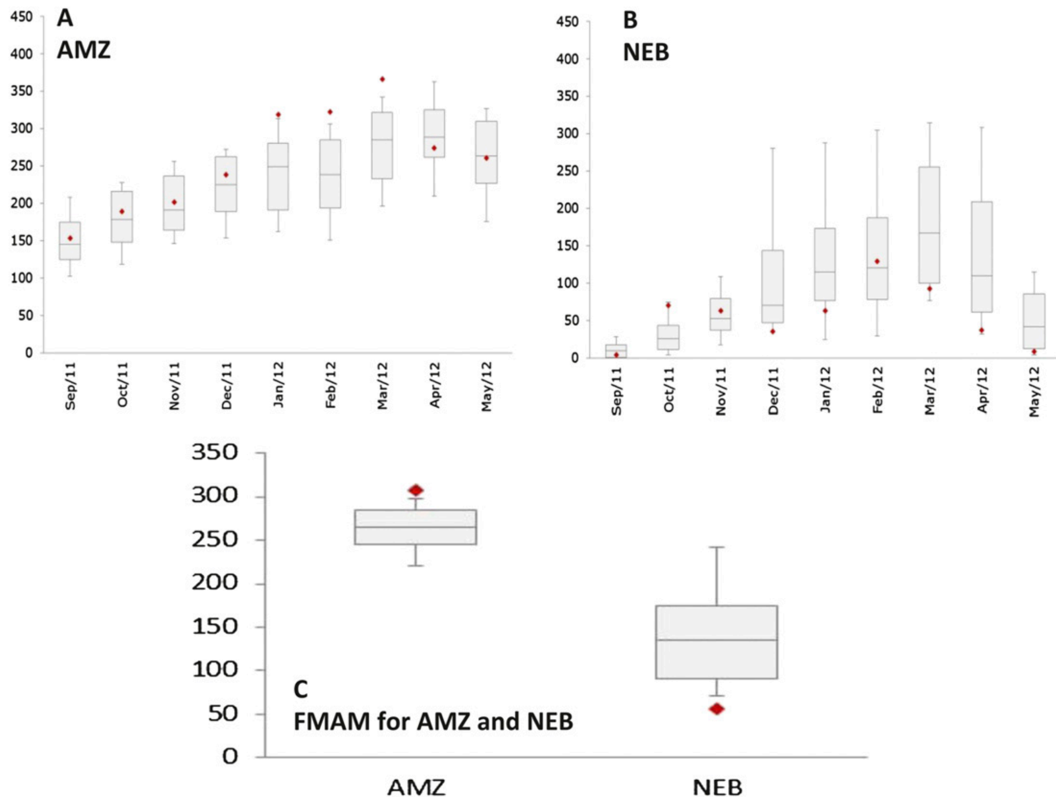

FIG. 6. Box plot diagram using the historical data (1961–2012) in two selected regions: (a) central-western AMZ and (b) NEB. Units are in millimeters per month.

those regions. At the monthly level (Figs. 6a,b), the observed means in 2011/12 are in general close to extreme values mainly during January–March (i.e., the historic maxima in central-western Amazonia and minima in Northeast Brazil), suggesting that the precipitation observed in 2012 in both regions was in fact extreme. The other interesting aspect is that over the Amazonia the values of precipitation exceeded the median rainfall since September 2011. It is clear also that over Northeast Brazil the precipitation had the greater variability, more than that over central-western Amazonia as indicated by the length of the bars.

We also present some details about the spatial distribution of rainfall extremes for the FMAM 2012 season (Fig. 7) and a statistical analysis of distributions based on GPCC data. The characterization for FMAM 2012 was performed using the quintiles (Q) method developed by Xavier et al. (2002). Following this approach, the conditions in FMAM 2012 were estimated for grid boxes based between the 15th and 85th percentiles (calculated with respect to 1971–2000). Color coding of the grid cells on the map (Fig. 7) facilitates the interpretation of the overall results. For example, cells in the driest 15th percentile (Q0.15) in FMAM 2012 are shaded in red, while the wettest cells (values in the 85th percentile; Q0.85) are shaded in blue. The thresholds for each of the other classes are represented by the following conditions: dry (from 15th to 35th), normal (from 35th to 65th), and wet (from 65th to 85th).

Figure 7 shows that during FMAM 2012, the western Amazon region was the wettest and Northeast Brazil was the driest. The distribution shows a clear predominance of very wet conditions in Amazonia and very dry conditions over Northeast Brazil. This reflects the atmospheric circulation behavior in the entire the region (Figs. 3 and 4) and is spatially consistent with the rainfall anomalies discussed in Fig. 5. This figure is intended to highlight the broad configuration of rainfall anomalies in tropical South America, while the percentile distribution from Fig. 7 shows the actual rainfall category (from very wet to very dry conditions) at individual locations more precisely.

6. Long-term hydrometeorological variability and trends

Figure 8 shows time series of SST anomalies in the tropical South and North Atlantic, the Niño-3.4 regions

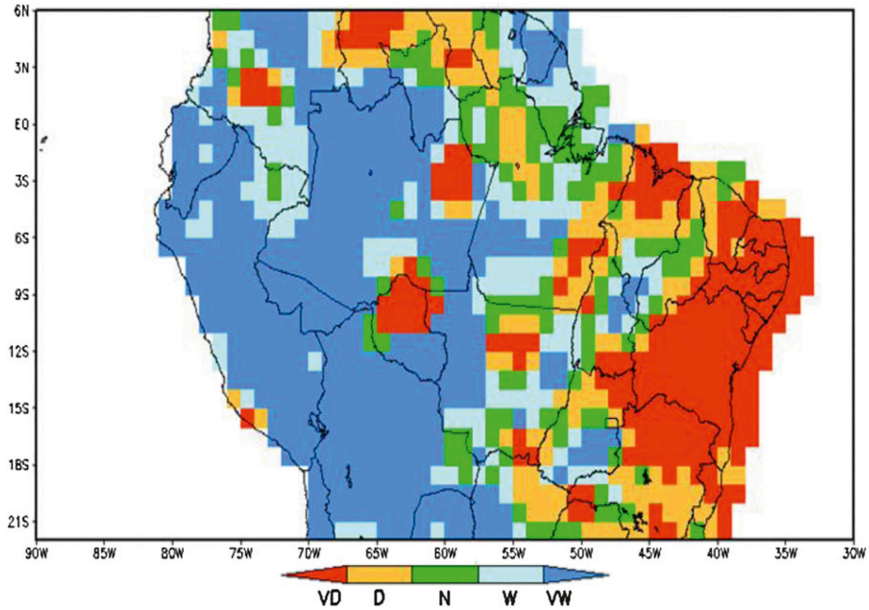

FIG. 7. Spatial distribution of the observed GPCC precipitation for FMAM 2012 categorized into five class intervals for the historical period 1961–2012. Colors represent the thresholds of each category: very dry (VD; less than Q0.15; red), dry (D; between Q0.15 and Q0.35; orange), normal (N; between Q0.35 and Q0.65; green), wet (W; between Q0.65 and Q0.85; blue), and very wet (VW; greater than Q0.85; dark blue) conditions.

in the equatorial Pacific, rainfall records during the peak season in western Amazonia and Northeast Brazil, and the mean annual and seasonal (peak season) levels for the Rio Negro at Manaus and the Amazon River at Iquitos and Santa Rosa.

Changes in patterns in the tropical Atlantic SST meridional gradient suggest a decadal variability, with changes in the mid-1940s and mid-1970s, which in turn are responsible for rainfall anomalies in the Amazon and Northeast Brazil regions, particularly during austral summer and autumn (Marengo 2004; Andreoli and Kayano 2007; Kayano and Andreoli 2004). However, neither the tropical North nor South Atlantic were very warm in 2012, and even though the Niño-3.4 SST anomaly series show a positive trend since the mid-1970s, La Niña conditions prevailed during the summer and fall of 2012.

In general, a weak positive/negative tendency during the peak of the rainy season (FMAM) is noticed in Amazonia/Northeast Brazil and is apparent since the late 1970s. These trends seem to be related to interannual rainfall variability rather than to a gradual unidirectional change in rainfall. The unprecedented high/low rainfall anomalies during 2012 in Amazonia/Northeast Brazil should be noted; these were the greatest departures from the mean during the last 40 years. In Northeast Brazil, where the FMAM peak season climatology from 1961 to 1990 is 125.3 mm, the five driest years were 1970 (71.7 mm), 1993 (73.6 mm), 1998 (75.3 mm), 2002 (76.2 mm), and 1992 (80.7 mm). The year 2012 set a new record low with 54.7 mm. For the Amazonia region, the three wettest years during the FMAM peak rainy season period during 1961–2012 (the 1961–90 mean is 263.9 mm) were 2011 (303 mm), 2009 (303 mm), and 1999 (299.4 mm). Other records were set in 1953 (306.9 mm) and 1955 (304.8 mm). Rainfall during FMAM 2012 in Amazonia was 344.2 mm—the highest ever recorded. Other rainfall records were 1962 (297.2 mm), 2000 (296.5 mm), 2006 (292.8 mm), and 1970 (292.1 mm). It can be seen from Fig. 8 that changes in river levels are not proportional to the magnitude of the rainfall anomalies, and in one or more sections of the Amazonia rivers, short- or long-term changes in flow cannot be explained in terms of rainfall variability alone (Sternberg 1987; Marengo et al. 2001; Tomasella et al. 2011).

Water level anomalies for the AMJ peak season reached the highest positive values in Iquitos and Santa Rosa, in the Peruvian Amazon, in Manaus, and in the Rio Negro basin in 2012 following the extreme precipitation anomalies observed earlier in northwest-central Amazonia. At the Manaus station, which has the longest available record of water levels for the Amazon basin (since 1903), the number of extreme positive anomalies seems to have increased since 1970 while the number of

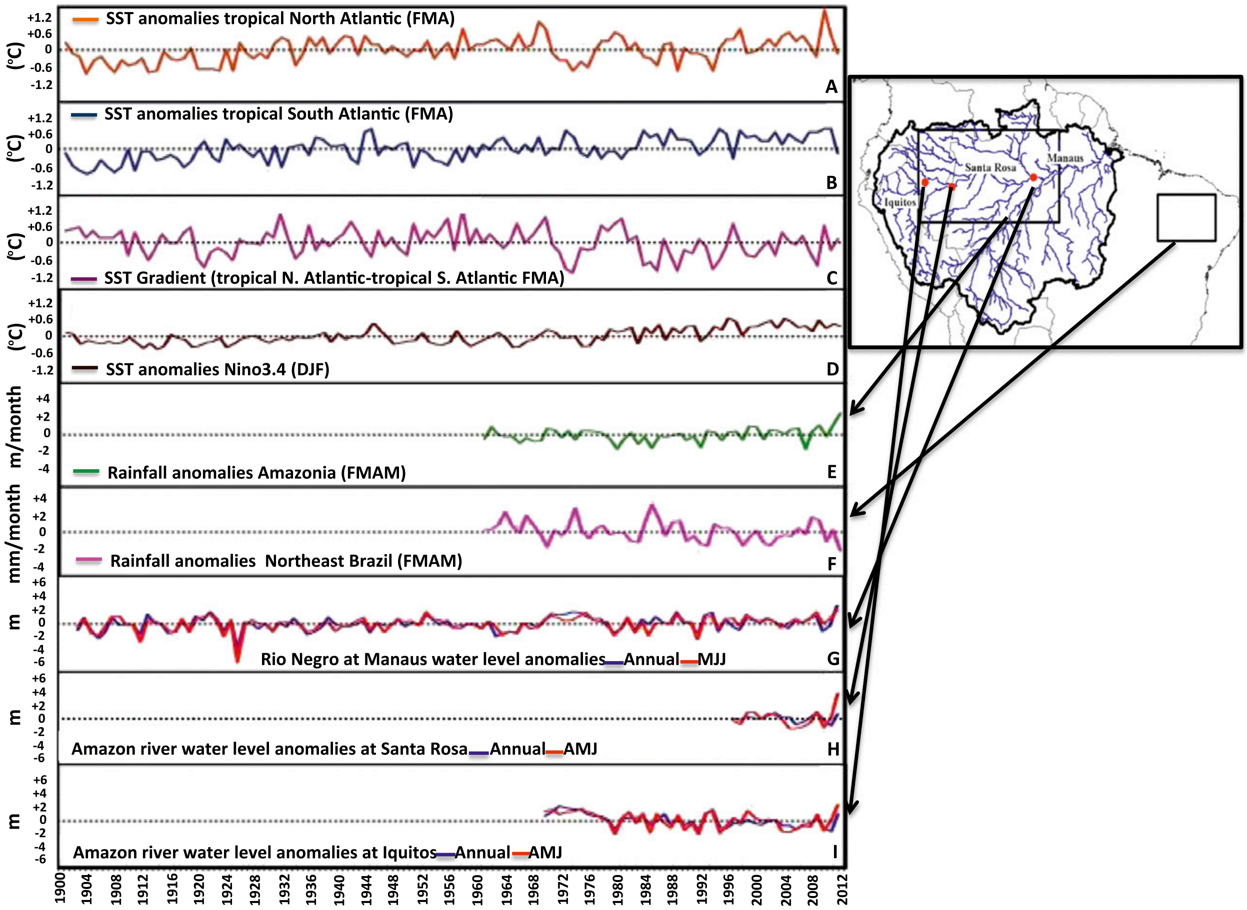

FIG. 8. Seasonal time series of SST anomalies (°C) in (a) tropical North Atlantic [February–April (FMA)], (b) tropical South Atlantic (FMA), (c) SST gradient between tropical North and South Atlantic (FMA), and (d) SST anomalies from the Niño-3.4 region for DJF for 1903–2012. GPCC-based rainfall (mm month^{-1}) in (e) central-western AMZ and (f) NEB for the peak of the rainy season (FMAM) for 1961–2012. (g) Mean annual and seasonal (MJJ) level anomalies (m) of the Rio Negro in Manaus for 1903–2012. (h) Mean annual and seasonal (AMJ) level anomalies (m) of the Amazon River at Santa Rosa for 1997–2012. (i) Mean annual and seasonal (AMJ) anomalies (m) at Iquitos for 1969–2012. Map with location of AMZ and NEB and the gauge sites appears to the right of the panels.

extreme negative anomalies decreased [see Fig. 3 in Marengo et al. (2011)].

The unilateral Bernoulli test for proportions applied considering proportions of the events for the 1903–69 (p1) and 1970–2012 (p2) periods rejects the null hypothesis of equal proportions of occurrence of events with anomalies greater than one standard deviation, at the 0.01 significance level, in favor of the alternative hypothesis ($p2 > p1$). On the other hand, the null hypothesis is rejected at the 0.05 confidence level for the proportions of events with anomalies of less than one standard deviation, which is the alternative hypothesis $p2 < p1$. In summary, the period 1970–2012 exhibits more flood events and fewer droughts events compared to 1903–69, based on water level anomalies at Manaus.

Early rains in spring 2011 in western-central Amazonia resulted in higher–than-average discharges since December 2011 and drove hydrographs to peak in a faster-than-average time in 2011 in Santa Rosa and Iquitos in 2012 (Fig. 9). In Manaus, the Rio Negro water levels were above normal since January 2012 and peaked one month earlier than the average. This could affect the main stem hydrodynamics downstream (Tomasella et al. 2013) and may have contributed to the historic flood in 2012 measured at the Manaus gauge station. Historical records at this station show few years when maximum levels were reached during May (1915, 1941, 1958, 1969, and 1992), but rainfall during these years was closer to, or lower than, the average.

For a different perspective, Fig. 10 shows bar diagrams of the number of rainfall extreme events defined using the GPCC seasonal precipitation in FMAM from 1961 to 2012 over central-western Amazonia and Northeast Brazil. Rainfall extremes were computed following

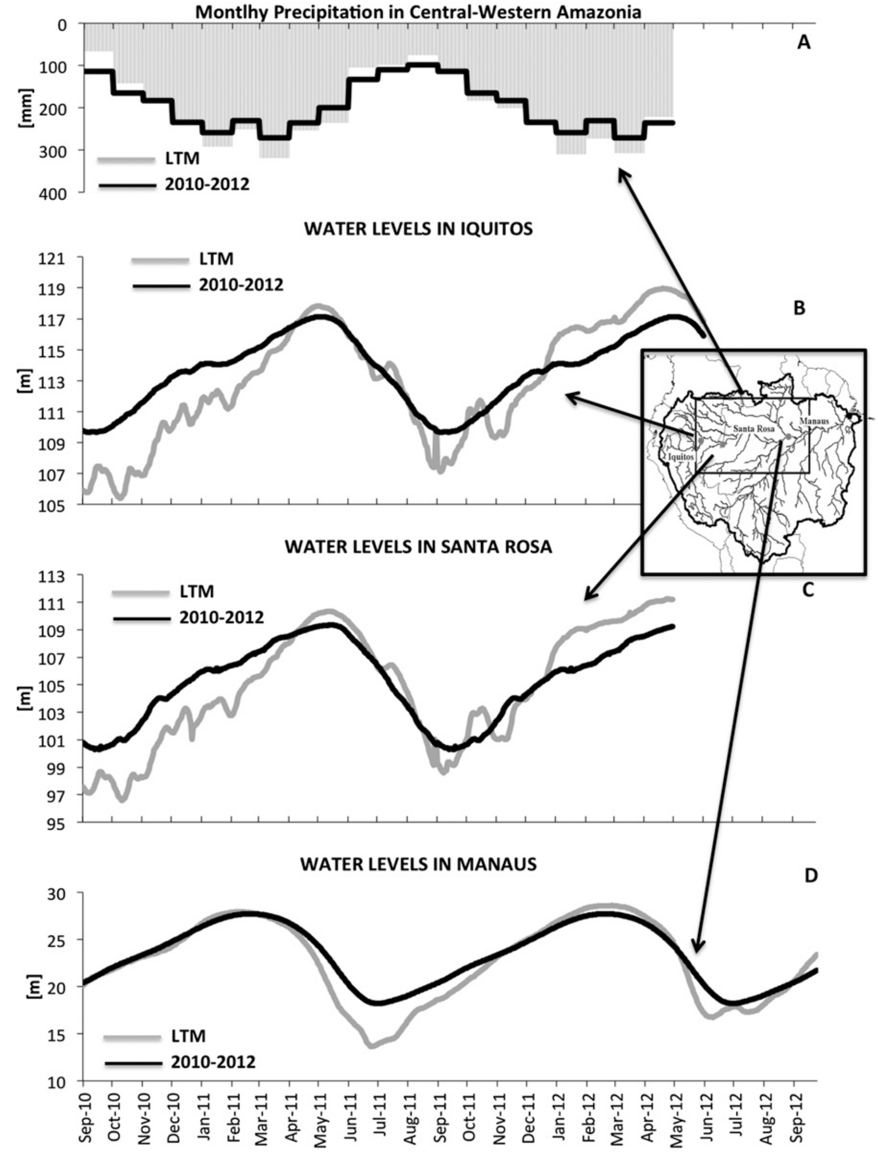

FIG. 9. Time series during 2010–12 in AMZ. (a) Monthly GPCC rainfall for central-western AMZ (mm) for LTM 1961–2012 and Sep 2010–Nov 2012 (mm), (b) monthly-mean levels at Iquitos (m) for LTM 1969–2012 and Sep 2010–Nov 2012, (c) monthly-mean levels of the Amazon River at Santa Rosa (m) for LTM 1997–2012, and (d) monthly-mean levels of the Rio Negro in Manaus (m) for LTM 1903–2012 and Sep 2010–Nov 2012. Map with location of AMZ and NEB and the gauge sites appear to the right of the panels.

Xavier et al. (2002). A regional frequency analysis was carried out to determine the number of each category of event over a 51-yr period, splitting the record into 5 separate decades. In Fig. 10, the bars reflect the frequency of events with very wet conditions in Amazonia and very dry conditions in Northeast Brazil for FMAM; the lines represent the numbers of seasons with opposite conditions in the two regions: very wet or wet in Amazonia and very dry or dry in Northeast Brazil (green line) and very dry or dry in Amazonia and very wet or wet in Northeast Brazil (purple line).

The most distinctive characteristic in Fig. 10 is the increase or decrease in variability of the wet conditions in Amazonia in the last decade (2000–12), where record floods were observed in 2009 and 2011 (Marengo et al. 2012; Espinoza et al. 2011). However, from the analysis of river data, there is no indication that more floods may occur in the coming years. In Northeast Brazil, the

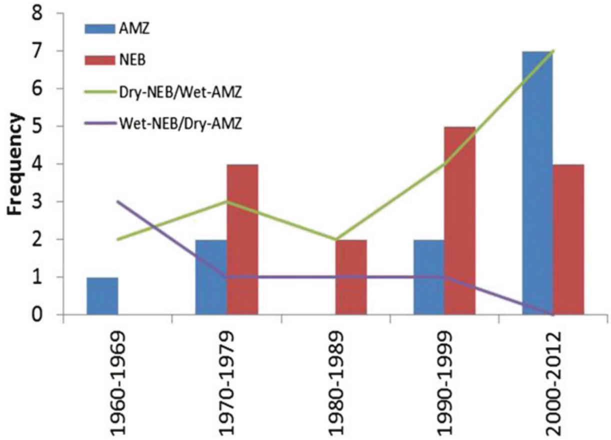

FIG. 10. Frequency distribution of number of extreme rainfall events characterized by dry events (red bar) for NEB and wet events (blue bar) for AMZ; number of the simultaneous events following dry (NEB) and wet (AMZ) conditions independent of the magnitude (green line) and opposite conditions (purple line). Precipitation data are from GPCC.

number of dry events does not exhibit a clear tendency, even though the last decade has slightly more events than in 2000–12. Although one cannot attribute those trends in extremes to climate change as such, the tendencies are consistent with global warming conditions [i.e., a higher frequency of extreme events; Seneviratne et al. (2012)].

7. Conclusions

Brazilian news broadcasts by the press and government agencies labeled the 2012 floods in Amazonia and drought in Northeast Brazil as the most severe in the last decades, and many districts in Amazonia and Northeast Brazil states declared a disaster area, mainly in the flood plains in Amazonia and the semiarid lands of Northeast Brazil. Governmental action during these extremes was in response to the emergency created by floods and droughts in 2012, with impacts on the local urban and rural residents in Amazonia related to the severe rise in the water level in the main stem and, on the other hand, drought-related impacts on small farmers and on food supplies in the cities in Northeast Brazil.

Changes in atmospheric circulation and rainfall are consistent with the notion of an active role of colder-than-normal surface waters in the equatorial Pacific, with above-normal upward motion and rainfall in western Amazonia, a typical atmospheric convection response to cold SST in the tropical Pacific. These patterns contribute to an intensified atmospheric transport of Atlantic moisture into the western part of Amazonia and then turning to southern Amazonia, where the Chaco low was intensified. The upper-level divergence–convergence circulation exhibited increased divergence over Amazonia and increased convergence over Northeast Brazil, with an intense rising motion in western Amazonia during austral summer and anomalous subsidence over Northeast Brazil during austral fall of 2012.

Over the subtropical South Atlantic, the anomalously cold surface water (2°C below normal) between 15° and 30°S during September 2011 and later on during March–May 2012 induced an intensification of high pressure in the South Atlantic, when the anomalously cold waters in the South Atlantic migrated northward (10°–20°S) in turn causing northward displacement of the high pressure areas that reached parts of Northeast Brazil. Subsequently, this high pressure interacted with the subsidence induced by the strong upward motion in Amazonia, determining dry conditions in Northeast Brazil. This is consistent with the wave train emanating from the equatorial Pacific as identified by Espinoza et al. (2013).

The mechanisms controlling the hydroclimatic dynamics of the study region during 2012 in fact involve local and remote influences during the spring and summer seasons, and that relationship involves precipitation and low-level circulation anomalies and soil moisture conditions. Furthermore, the higher levels of Amazonian rivers in 2012 were due to the greater persistence associated with extreme rainfall that generated higher streamflow. There is a nonlinear relationship between runoff and precipitation owing to the effects of soil saturation.

This situation detected in the tropical South Atlantic in 2012 was not observed during other wet years in Amazonia such as 1989, 1999, and 2009 but was observed in the dry years of 1958/59 in Northeast Brazil. In that sense, cold surface waters in the tropical Pacific during La Niña could be indicated as the main cause of the abundant rainfall in western Amazonia from October to December 2011, remaining mostly in central Amazonia until May 2012. The anomalously high water levels in Amazonian rivers during January–May 2012 and later on were because rainfall in the western basin was more abundant during October–December, with an early onset of the rainy season as in 2009.

In Northeast Brazil, dry conditions started to appear in December 2011 in the northern sector and then extended to the entire region by the peak season February–May 2012 due to an active role of the South Atlantic high pressure system, which was intense and closer to the continent, determining low-level subsidence and together with anomalously downward motion impacted the rainfall regime in Northeast Brazil.

The ostensibly large number of seasonal hydrological extreme events during the last seven years in tropical

South America, particularly in the Amazonia region, has triggered intensive discussions on whether the fact of having two extreme droughts in 2005 and 2010 and two extensive droughts in 2009 and 2012 is related to global warming. SST and anomalous atmospheric circulation patterns can greatly exacerbate the intensity and frequency of such extreme events and may also explain some observed outliers.

In historical terms, events in which Amazonia is wet and Northeast Brazil is dry have not occurred very frequently, as compared to situations with dry Amazon/wet Northeast Brazil, and they have been more frequent during 2000–12, perhaps dominated by the intense floods of Amazonia in 2009, 2011, and 2012. However, the 2012 events were the most intense since 1960, and these two extremes in 2012 were worse than the previous record drought in Northeast Brazil in 1998 and the previous record flooding in Amazonia in 2009.

Further analysis is needed to understand the mechanism responsible for connecting the Amazonia and Northeast Brazil rainfall and tropical and subtropical Atlantic–equatorial Pacific SST. These extremes seem to be part of the natural climate variability and drought and floods in the tropical south, linked to changes in the large-scale circulation on interannual time scales and attributed to particular signals in tropical and subtropical oceans.

At this stage it is not possible to attribute these observed long-term rainfall changes in Amazonia and Northeast Brazil to land use change because they occur at interannual time scales, where signals of land use changes and land surface processes are not noticeable.

On the role of land surface processes and land use changes in regional circulation, Angelini et al. (2011) found that rain in Amazonia comes primarily from large-scale weather systems coming from the tropical Atlantic and that it is not directly driven by local evaporation. On the other hand, Makarieva et al. (2013) suggest that the water vapor delivered to the atmosphere via evaporation from forests represents a store of potential energy available to accelerate air and thus drive winds. This implies that changes in precipitation over Amazonia are due to a combination of different regional processes and interactions that are partly influenced by large-scale circulation as well as by local water sources from forests and soil moisture.

Further work is required to assess the role of the various processes associated with both land surface feedbacks and SST forcing in determining rainfall variability in tropical South America to the east of the Andes at different time scales. For future climates, changes in precipitation and in its variability over Amazonia and Northeast Brazil may be a product of complex changes in large-scale circulation and local controls from vegetation, and judicious model experiments can help in understanding how those changes could affect climate and hydrology in both regions in the context of global warming.

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