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2014 Environ. Res. Lett. 9 124007

(http://iopscience.iop.org/1748-9326/9/12/124007)

OPEN ACCESS
IOP Publishing
Environmental Research Letters
Environ. Res. Lett. 9 (2014) 124007 (9pp)
doi:10.1088/1748-9326/9/12/124007

The extreme 2014 flood in south-western Amazon basin: the role of tropical-subtropical South Atlantic SST gradient

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Received 8 July 2014, revised 26 September 2014
Accepted for publication 18 November 2014
Published 8 December 2014

Abstract

Unprecedented wet conditions are reported in the 2014 summer (December–March) in South-western Amazon, with rainfall about 100% above normal. Discharge in the Madeira River (the main southern Amazon tributary) has been 74% higher than normal (58 000 $m^3 s^{-1}$) at Porto Velho and 380% (25 000 $m^3 s^{-1}$) at Rurrenabaque, at the exit of the Andes in summer, while levels of the Rio Negro at Manaus were 29.47 m in June 2014, corresponding to the fifth highest record during the 113 years record of the Rio Negro. While previous floods in Amazonia have been related to La Niña and/or warmer than normal tropical South Atlantic, the 2014 rainfall and flood anomalies are associated with warm condition in the western Pacific-Indian Ocean and with an exceptionally warm Subtropical South Atlantic. Our results suggest that the tropical and subtropical South Atlantic SST gradient is a main driver for moisture transport from the Atlantic toward south-western Amazon, and this became exceptionally intense during summer of 2014.

S Online supplementary data available from stacks.iop.org/ERL/9/124007/mmedia

Keywords: extreme flood, Amazon basin, Madeira river, Bolivian Amazon, Brazilian Amazon

1. Introduction

Several extreme hydrological events have been reported in the Amazon region during the last decade (Marengo *et al* 2011, 2012, 2013, Espinoza *et al* 2011, Satyamurty *et al* 2013). Abundant rainfall, especially in the western Amazon, has caused intense floods along the rivers main channel, affecting human and natural systems (Marengo *et al* 2012, 2013, Espinoza *et al* 2013). This is consistent with a possible intensification of the hydrological cycle in western Amazon detected since the beginning of the 1990s, characterized mainly by an increase in rainfall amount in that part of the basin (Espinoza *et al* 2009a, Lavado *et al* 2012, Gloor *et al* 2013). Some of these intense rainfall and subsequent floods were associated with La Niña events (e.g. 1989, 1999, 2009, 2011 and 2012) and characterized by an abundant moisture transport flux from the tropical North Atlantic and the Caribbean Sea toward the north-western Amazon and a maintenance of the monsoon flux over this region (Espinoza *et al* 2012, 2013). Intense rainfall over the central Amazonia and extreme floods have been also related to an anomalously southward migration of the Atlantic ITCZ, in relation to warm conditions in the tropical South Atlantic sea surface temperature (SST), as observed in 2009 (Marengo *et al* 2012, 2013). The flood of 2012, a record during the last 50 years, was related to both La Niña and warm conditions in the tropical South Atlantic (Marengo *et al* 2013, Espinoza *et al* 2013). However, in the 2013–14 austral summer (December–March), the Madeira basin in south-western Amazon experimented historical rainfall and flood, while no robust SST anomalies were observed in El Niño regions and in the tropical Atlantic ocean. That is why this event deserves further attention.

In south-western Amazon, the Madeira River basin is characterized by a wet season in early austral summer, related to the presence of the South Atlantic Convergence Zone (SACZ), an integral component of the South America Monsoon System (SAMS) (Vera *et al* 2006, Marengo *et al* 2011). In the upper Madeira basin (Mamoré basin), abundant rainfall and floods have been related to a weak meridional SST gradient in the southern Atlantic (Ronchail *et al* 2005); however, the atmospheric processes associated with these SST anomalies remain undocumented. Moreover, during no El Niño years this gradient modulates the cyclogenesis and rainfall variability in eastern South America and along the SACZ (Bombardi *et al* 2014).

Higher than normal precipitation was observed from September 2013 and they became very intense at the end of January and beginning of February 2014 on the eastern flank of the Andes and in the lowlands east of the Andes (figure 1(c)). Extreme rainfall produced inundations and landslides in several cities of Bolivian and southern Peruvian Amazon (e.g. in the upper Beni River, figure 1(b)), affecting about 68 000 families, while more than 60 people had died in Bolivia. Also, about 40 000 hectares of crops was damaged. The Bolivian and Peruvian Governments declared a national state of emergency on 27 January and on 3 February, respectively.

In February 2014, floods affected the Brazilian states of Acre and Rondonia, where was reported the highest historical discharge in the Madeira River. Indeed, at Porto Velho station 56 000 $m^3 s^{-1}$ were reported, instead of the climatological discharge maximum of 38 000 $m^3 s^{-1}$ (figure 1(a)). It is also noticeable that this maximum generally occurs in April (and not in February). Then, March the 27th, Porto Velho station reached its historical discharge of 58 000 $m^3 s^{-1}$ (figure 1). According to Brazilian newspapers and government assistance agencies, the government declared state of emergency in the state of Acre, where the capital Rio Branco remained isolated during nearly two months by the rise of the river level that flooded the main roads and affected the transportation of food and fuel into the city. By June 2014, the city of Manaus was under an emergency situation due to a flood situation.

This work aims to describe and analyse the meteorological and hydrological characteristics and impacts of the unprecedented 2014 high-water period in the Madeira River, the main south-western Amazon tributary (955 000 km^2 at Porto Velho station), and compare the climate features of this event with previous recent flood events.

2. Hydro-climatic data sets

In situ daily rainfall information was collected in the upper Madeira basin (Bolivia) from the national meteorological services (SENAMHI) of Bolivia and Peru. Rurrenabaque and Trinidad stations were selected considering their temporal continuity and data quality for the 1950–2014 period. Moreover, estimation of regional rainfall anomalies during November 2013–April 2014 were obtained form TRMM-RT 3B43 V7 product (Huffman *et al* 2007) with a 0.25° spatial resolution. The period used for computing the climatology is 2000–2013. In addition, we also analyse monthly rainfall information form the Global Precipitation Climatology Project (GPCP) (Adler *et al* 2003) available from January 1979 to march 2014 at a 2.5° resolution (www.esrl.noaa.gov/psd/).

The National Meteorology and Hydrology Services in the region (SENAMHI of Bolivia, National Water Agency (ANA) of Peru and Brazil) provided high quality daily water level data for the lower and upper Madeira basin (figure 1(d)), including data at Porto Velho (Madeira River), Rurrenabaque (Beni River) and Guajara-Mirim (Mamoré River). Rating curves were determined using acoustic Doppler current profiler (ADCP) gauging measures, conducted by the ORE-HYBAM observatory (www.ore-hybam.org). Daily discharge values are available since 1967 in Porto Velho and Rurrenabaque stations, while since 1971 in Guajara-Mirim station. The locations of hydrological and rainfall stations are displayed in figure 1(d).

Oceanic and atmospheric features are analysed using the global monthly SST data available at 2° resolution (Reynolds and Smith 1994) from the NOAA-CPC and the 2.5° resolution horizontal winds, geopotential height, and specific humidity data from the NCEP–NCAR reanalysis (Kalnay *et al* 1996). The vertically integrated water vapour flux and its divergence are derived from the specific humidity and the horizontal wind considering 1000, 925, 850, 700, 600, 500, 400 and 300 hPa pressure levels (Peixoto and Oort 1992).

3. Hydrometeorological characteristics of the 2013–14 rainy season

Regional TRMM-RT rainfall anomaly maps (figures 2(a)–(f)) show abundant rainfall over the Madeira River basin in the southwestern Amazonia, since November 2013 in the southern Mamore sub-basin and since December, northward, in the sub-basins of the Beni and Madre de Dios rivers. From December 2013 to January 2014, the anomalous rainfall increased by 5–10 mm day^{-1} over the Madeira basin. The positive rainfall anomalies extended to western Amazonia over most of the Solimões River basin in January and over eastern Amazonia in February 2014. This is consistent with rainfall anomaly maps elaborated by CPTEC INPE (www.cptec.inpe.br) that show rainfall anomalies reaching 80–100% above normal over northern Bolivia and Rondonia (Brazil) in December 2013–January 2014, and between 40–80% above normal in eastern Amazonia in February 2014. In March 2014 the rainfall anomalies were mostly concentrated in Bolivia

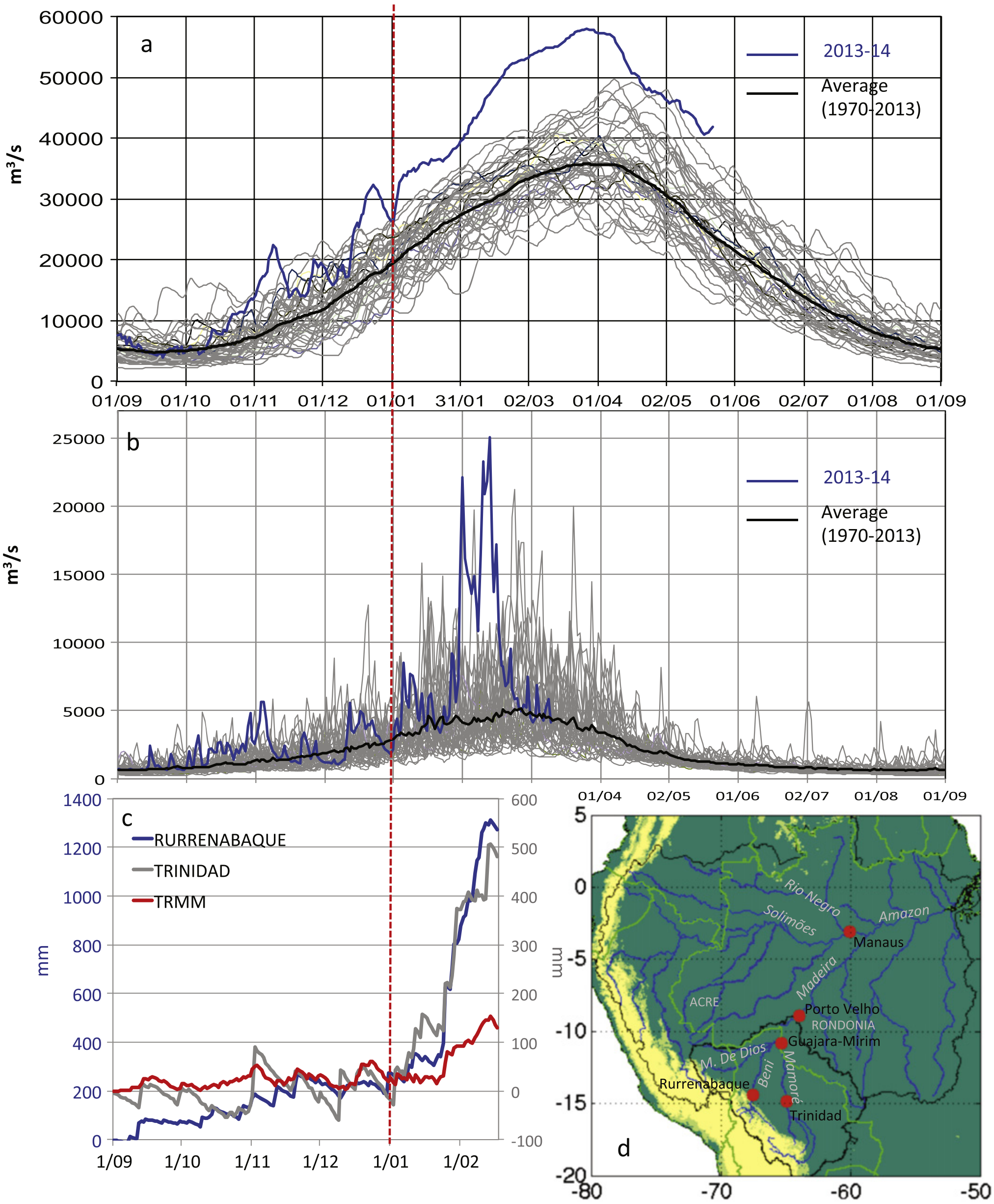

Figure 1. Daily discharge at (a) Porto Velho and (b) Rurrenabaque stations during the 1970–2013 period (grey lines), mean hydrological year (black line) and discharge during the 2013–14 hydrological year (blue line). (c) Cumulative rainfall anomalies in Rurrenabaque (blue, left *Y* axe) and Trinidad (grey, right *Y* axes) and area average rainfall in Porto Velho River basin estimated from TRMM-RT 3B42 V7 (red, right *Y* axe), for the 01/09/2013–17/02/2014 period. Rain gauges and TRMM anomalies are computed considering the 1950–2013 and 2000–2013 periods, respectively. (d) Situation of hydrological and rainfall stations (red dots). The names of the main rivers are indicated in grey-italic and the names of the states are indicated in grey-capital letters. Countries limits are represented by green lines and the boundary of the upper Madeira basin by a black line.

(Mamore basin) and in April 2014 rainfall was around normal in the entire basin, while in May 2014 rainfall was above normal over Bolivia/Paraguay and northern Argentina.

At the regional level, accumulated rainfall from 01/09/2013 to 17/02/2014 was 31% above normal in Trinidad in the Bolivian Llanos and 108% in Rurrenabaque, east of the Andes. January and February 2014 (until the 17th) 2014 were the rainiest periods since the beginning of the observations in both stations (1944), where around 300 mm is usually observed during January or February. In Rurrenabaque, 1100 mm were recorded between January the 24th and February the 10th (figure 1(c)); around four times the mean January or February rainfall. Both the TRMM derived maps from figures 2(a)–(f) and the regional records suggest that while moderate positive rainfall anomalies were reported since November 2013, very wet condition suddenly appeared toward the end of January 2014.

The rainfall anomalies during early austral summer 2013–2014 in south-western Amazonia impacted the hydrological regime across the basin. In the hydrological Rurrenabaque station (upper Beni River), that mainly drains Andean regions, discharge reached 25 000 $m^3 s^{-1}$ February

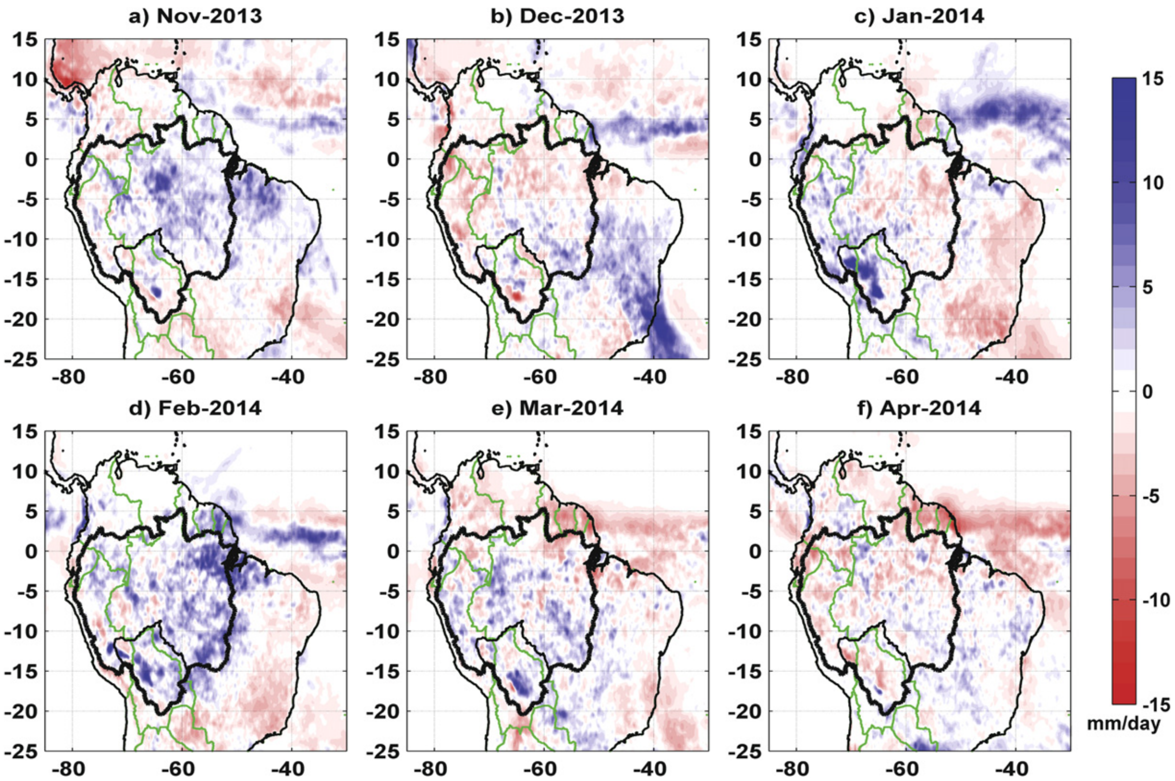

Figure 2. Rainfall anomalies (mm/day) estimated for TRMM-RT from (a) November 2013 to (f) April 2014. Anomalies are computed considering the 2000–2013 climatology. Countries limits are represented by green lines and the boundary of the upper Madeira basin by a black line.

the 12th (380% above normal), which is the highest observed value (1967-present; figure 1(b)). Discharge values exceeding 10 000 $m^3 s^{-1}$ (twice the mean discharge of January or February) have been observed during 18 days. Discharge anomalies in the Mamore basin in Guajara-Mirim began sooner, in November, and since then, they are 2000 to 3000 $m^3 s^{-1}$ over the normal; for instance 14 000 $m^3 s^{-1}$ have been recorded in February 2014 instead of 11 000 (not shown).

Heavy rainfall and high discharge values in all the upper sub-basins of the Madeira River also impacted discharge downstream, generating positive discharge anomalies since November 2013 at Porto Velho hydrological station and an unprecedented and continuous discharge increase since mid January 2014 until March 2014 (figure 1(a)). Moreover, flooding in Porto Velho during 2013–14-summer season was exceptionally earlier than normal because of the intense rainfall in December 2013–January 2014 over the southwestern Amazonia, suggesting also an early start of the rainy season in this region. Indeed, discharge in Porto Velho in February (53 200 $m^3 s^{-1}$) was 40% higher than the usual peak (1970–2013) that occurs in April (mean of 38 000 $m^3 s^{-1}$) and 74% higher when compared to the mean February discharge (mean of 30 500 $m^3 s^{-1}$).

Historical discharge values have been registered until May in Porto Velho (figure 1(a)). This unusual runoff probably caused a backwater effect upstream the confluence between the Madeira River and the main channel of the Amazon River (Cappelaere *et al* 1996). This, along with higher than usual precipitations in the Negro and Solimões basins, may have contributed to trigger flooding in Manaus (less than 200 km from the confluence Madeira-Amazon; figure 1(d)). Indeed, the Brazilian Geological Survey CPRM (www.cprm.gov.br) reported that the levels of the Rio Negro at Manaus reached by 12 June the level of 29.47 m, flooding some parts of the downtown Manaus city, and determining state of emergency in this city by the Amazonas State government. This level corresponds to the fifth highest record during the 113 years record of the Rio Negro, and this was 50 cm below the highest record since 1903 measured in July 2012 (Marengo *et al* 2013). It is important to note that water level in Manaus is also controlled by the backwater effect of the Solimões River (Meade *et al* 1991).

4. Large-scale circulation features during the 2013–14 rainy season

December 2013 is characterized by positive SST anomalies in the western tropical Pacific and in the subtropical South Atlantic, while SST anomalies were weak in the tropical Atlantic and eastern Pacific. A SST gradient is noticed between the tropical and sub-tropical south Atlantic (hereafter TSA-SSA gradient). In January 2014, cold SST anomalies are observed over the central Pacific and around the southern tip of South America while warm SST anomalies characterize the

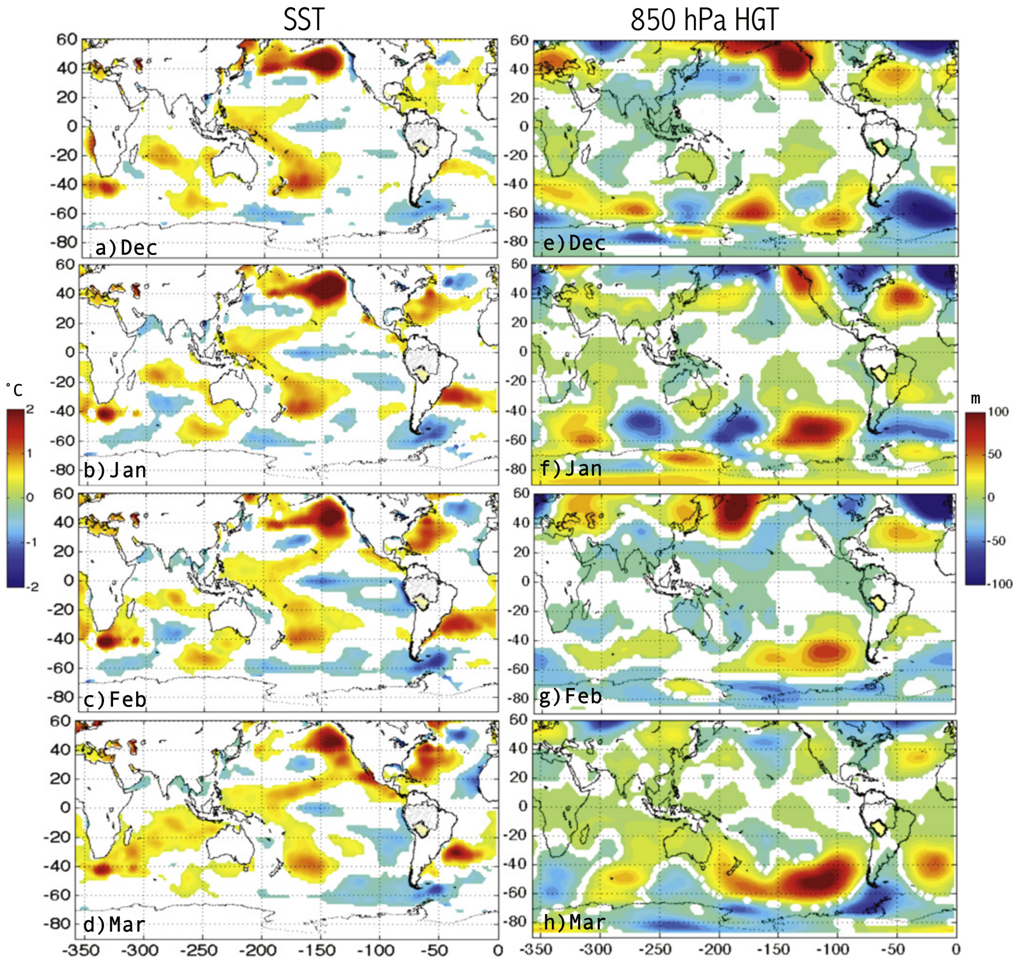

Figure 3. December 2013–March 2014 anomalies of SST ((a) to (d), in °C) and 850 hPa geopotential height ((e) to (h), in (m)). Anomalies are computed considering the 1970–2012 climatology. Only anomalies higher than 1× std (0.5× std) are plotted for SST (850 hPa geopotential) maps.

sub-tropical South Atlantic. The TSA-SSA SST gradient strengthened, in part due to strong warming conditions in SSA (figures 3(a)–(d)).

In December 2013 and January 2014, 850 hPa geopotential height (figures 3(e)–(h)) show positive anomalies over the southeastern Pacific and negative anomalies over the southwestern Pacific (south of Australia) and around the southern tip of South America; in January, they are over the subtropical South Atlantic. This may suggest the presence of a wave train that emanates from the western Pacific-Indian Ocean midlatitudes, then propagates toward South America, turning equatorward crossing the Andes around southern South America. This wave train is also remarkable in the upper troposphere at 200 hPa (not shown). This mechanism has already been documented by several works, which described the intraseasonal rainfall variability in subtropical South America (e.g. Nogués-Paegle and Mo 1997, Liebmann *et al* 1999, 2004, Diaz and Aceituno, 2003, Gan and Rao 1994, Vigliarolo and Berbery 2002, Vera *et al* 2006).

Though, a change in the height anomaly regime is noticed between December 2013 and January 2014; indeed, in December the negative height anomalies located over southeast South America show some resemblance to that related to the SACZ activity (Liebmann *et al* 1999, Doyle and Barros 2002). In fact, this is consistent with the intense cyclonic anomaly and increased moisture convergence over southeastern Brazil, during a SACZ episode over that region in December 2013 (figure 4(a)), responsible for the intense rains in the state Espirito Santo during the second half of the month (Marengo *et al* 2014). The atmospheric situation changed in January 2014 and persisted until March 2014. It is characterized by positive height anomalies, consistent with an anomalous anticyclonic circulation, that extends from a warmer than normal sub-tropical South Atlantic into South America between 10–40°S east of the Andes (figure 3(f)).

The vertically integrated vapour transport anomaly fields show that for December and January, while contrasting circulation patterns are detected over Southeastern Brazil, an intense moisture convergence is detected over western Amazonia-southern Andes region (figures 4(a), (b)). It is associated to intense northwesterly incursions of vertically integrated humidity transport from the tropical north Atlantic to southern Amazon and along the southern Andes in December and moisture transport from the tropical South Atlantic in January (figures 4(a), (b)). Enhanced convection in the downstream part of the South American Low Level Jet

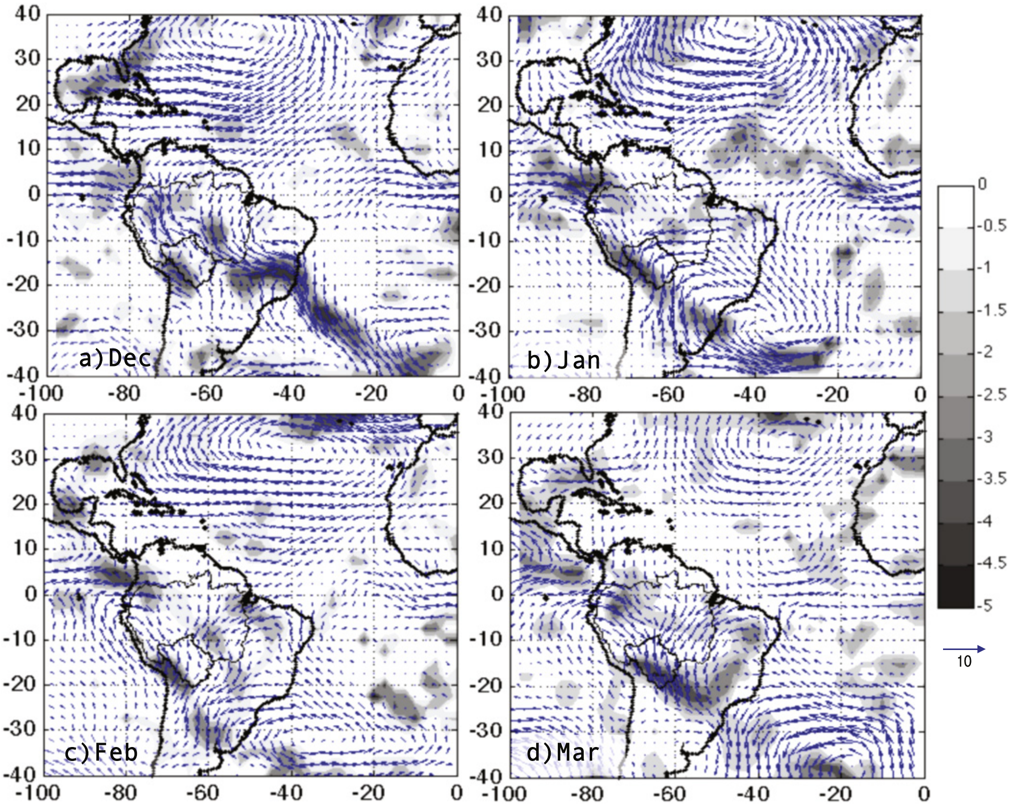

Figure 4. December 2013 (a) to March 2014 (d) anomalies of vertically integrated humidity transport flux (vectors, in kg m^{-1} day^{-1}) and standardized negative divergence values (grey shaded, without unit). Anomalies are computed considering the 1970–2012 climatology. A black line represents the boundaries of the Amazon and of the upper Madeira basins.

(SALLJ) and weak SACZ are responsible for the enhanced rainfall over western Amazonia-southern Andes during January 2014. As a consequence, unprecedented rainfall and discharge predominate in Madeira River and tributaries since January 2014 (figures 1, 2).

The 850 hPa geopotential height anomaly in the 20°S–35°S and 30°W–50°W region, which appears in January 2014, one month after positive SST anomaly over this region, was the highest recorded in the 1970–2013 period (figure S1). These climatic features are coherent with the beginning of positive rainfall anomalies observed over the Madeira River basin since the end of December 2013, and with a reduction of humidity transport from the Amazon to the La Plata basin, leading to record high rainfall in south-western Amazon, as reported by CPTEC INPE during January 2014. The strengthening of the negative TSA-SSA SST gradient suggests an intensification of the wave train over the South American sector, with more rainfall over western Amazonia-southern Andes and less rainfall in southeastern South America. Modelling experiment would be useful to verify the ocean-atmosphere mechanisms and their impacts on rainfall on the upper Madeira.

Extreme floods in Beni River at Rurrenabaque station (figure 5(a)), above 15 000 m^3 s^{-1}, are reported during La Niña years (e.g. 1971, 1999 and 2011) and also in absence of La Niña conditions (e.g. 1978, 1982, 2001 and 2014). In this section we analyse climatic features associated to floods occurring during no La Niña years, as they are less known than those occurring during La Niña.

December–February composite analysis (1978, 1982, 2001 and 2014) shows positive SST anomalies in western equatorial and south tropical Pacific, while a TSA-SSA SST gradient is observed (figure 5(b)). Positive 850 hPa geopotential height anomaly predominate in the SSA region (figure 5(c)), which is probably related to warm SST conditions in the SSA region (e.g. Chavez and Nobre 2004, Jorgetti *et al* 2014). These features enhance humidity transport flux from tropical South Atlantic to south-western Amazon-eastern Andes and strong convergence is observed over Bolivian and the South of Peruvian Amazon (figure 5(d)). Indeed, extreme flood events in the upper Beni River (1978, 1982, 2001 and 2014) are all characterized by strong positive 850 hPa geopotential height anomalies in the SSA region (figure S1). Comparing composites of humidity transport flux with those observed in 2013–14, we note that during December 2013 the incursion of humidity flux is more intense from the tropical North Atlantic to southern Amazon (figure 4(a)). These differences might explain the magnitude of 2014 flood in contrast to others no-La Niña floods events.

This circulation pattern over the SSA region and its consequence in rainfall over the upper Madeira River basin is consistent with intensity of the height anomalies over this region, with positive height anomalies over SSA, South Pacific around 100°W and over Australia, and negative height

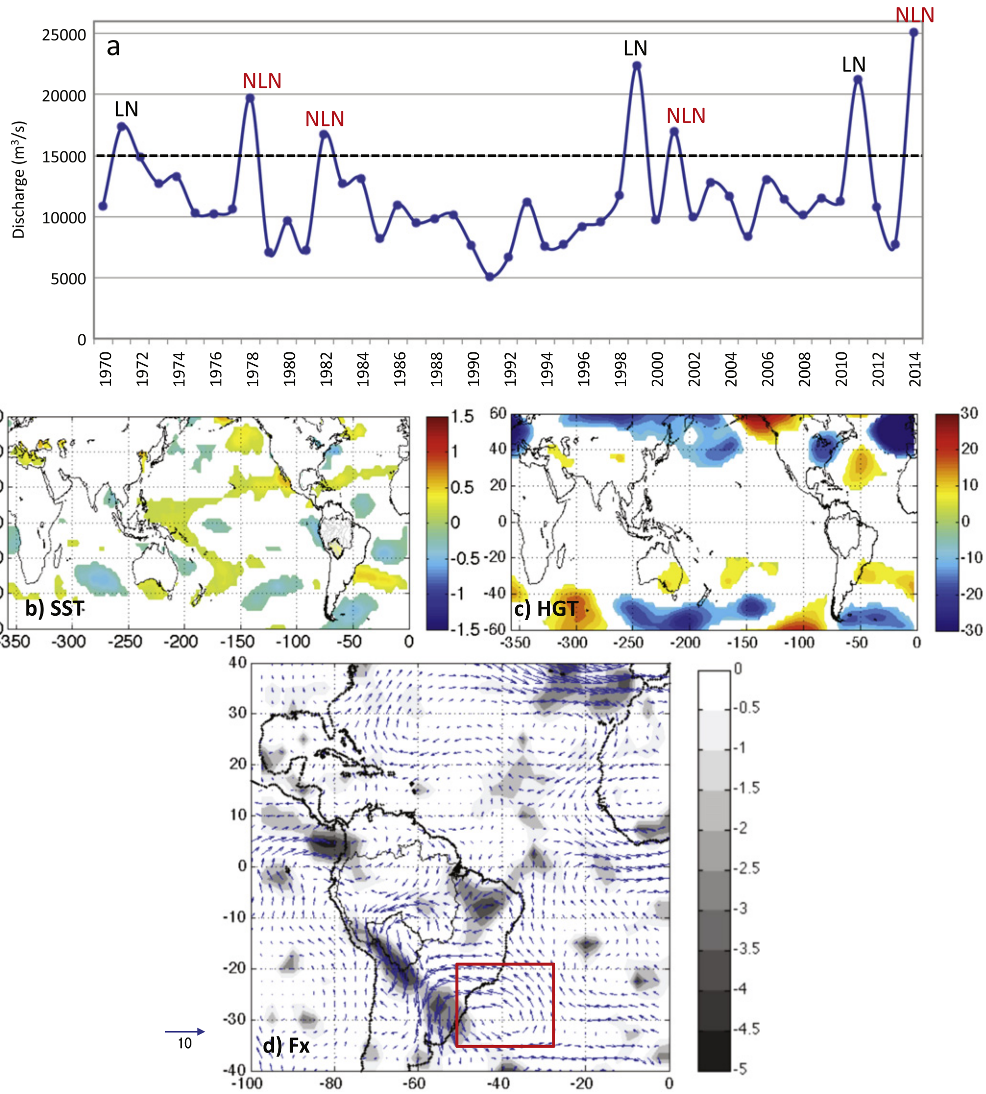

Figure 5. (a) Annual maximum discharge in Rurrenabaque station (upper Madeira). Composite analysis of (b) SST, (c) 850 hPa Geopotential height and (d) vertically integrated humidity transport flux (vectors, in kg m^{-1} day^{-1}) and standardized negative divergence values (grey shaded, without unit), during no La Niña extreme floods (1978, 1982, 2001, and 2014) (December (n–1)–February (n) average). A black line represents the boundaries of the Amazon and of the upper Madeira basins. Only values higher than 1× std are plotted in panels (b) and (c).

anomalies over the southern tip of South America and New Zealand, may indicate the propagation of the Rossby-type wave pattern during the austral summer (figures 3(e)–(h) and 5(c)). The circulation pattern over the Madeira basin linked to the positive height anomalies over SSA shows moisture flux from the South tropical Atlantic that converges with the northern flux along the Andes over the upper Madeira basin, as shown by figures 4 and 5(c).

The main ocean-atmospheric differences between floods not related to La Niña and those related to La Niña are displayed in figure S2. Compared to La Niña floods, warmer conditions are observed in the Indian Ocean and, as expected, in the equatorial Pacific during the 1978, 1982, 2001 and 2014 floods (figure S2(a)). Over the Atlantic Ocean a clear SST pattern is noticed, confirming a TSA-SSA SST gradient, with positive (negative) SST anomalies in SSA (TSA). Geopotential height differences at 850 hPa show again a train-wave with positive values over Australia, the South Pacific (around 70°S and 140°W) and over SSA (figure S2(b)). In accordance with the geopotential height anomalies, the advection of humidity transport flux is observed from the tropical South Atlantic to the south-western Amazon, producing abundant convergence of humidity transport flux over the upper Madeira basin (figure S2(c)). These results complement our findings about the particularities of the floods related to the TSA-SSA SST gradient in contrast with previous floods related to La Niña in northward regions (i.e. 1999, 2011, 2012) (Espinoza *et al* 2012, 2013, Marengo *et al* 2013) or to a cooler than usual tropical North Atlantic SST (i.e. 2009) (Marengo *et al* 2012).

In order to complement the results of the composite analysis, a December–February correlation analysis is computed between global SST and historical data from: (i) 850 hPa geopotential height in the SSA region (20°S–35°S and 30°W–50°W; figure 6(a)), (ii) convergence of humidity transport flux in the upper Madeira basin (12.5°S–20°S and

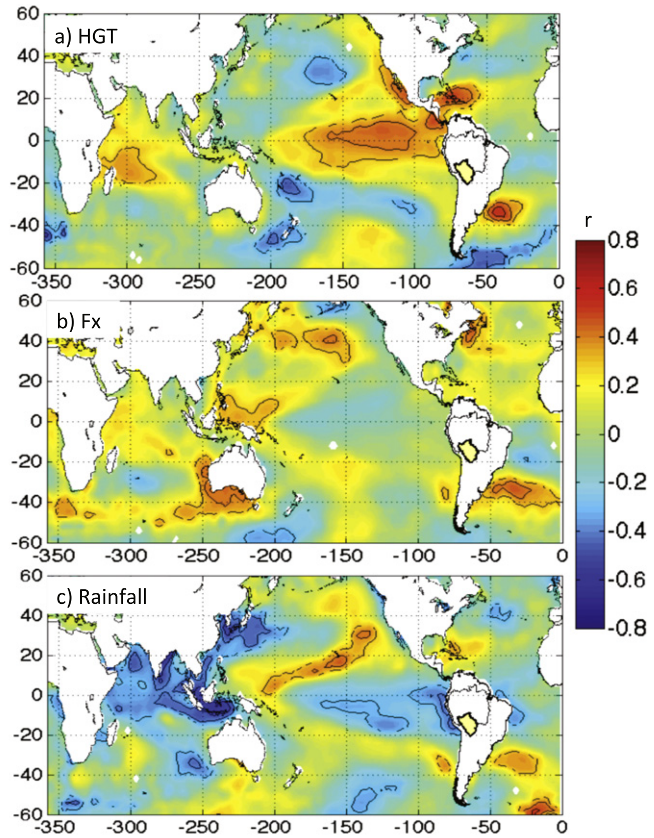

Figure 6. December–February correlations between SST and: (a) geopotential height in the 20°S–35°S and 30°W–50°W region (red box in figure 5(d)) during the 1970–2014 period, (b) convergence of humidity transport flux in the upper Madeira basin (12.5°S–20°S and 65°W–75°W) during 1970–2014 period and (c)) mean rainfall in the upper Madeira basin (12.5°S–20°S and 65°W–73.5°W) computed from GPCP for the 1980–2014 period. Values with $p < 0.1$ are marked with black line.

65°W–75°W; figure 6(b)) and (iii) mean GPCP rainfall in the upper Madeira River basin (12.5°S–20°S and 65°W–72.5°W; figure 6(c)). Results also indicate that warm conditions in SSA SST are significantly associated with positive 850 hPa geopotential height anomalies over SSA and South of Brazil ($p < 0.05$; figure 6(a)), which enhance humidity transport from tropical South Atlantic to the upper Madeira. Indeed, convergence of humidity transport flux from the tropical South Atlantic to the upper Madeira basin is significantly correlated with the TSA-SSA SST gradient; in particular, positive correlation appears between SSA SST and convergence of humidity transport flux and mean rainfall over Maderia basin ($p < 0.05$; figures 6(b) and (c), respectively). From the large-scale circulation patterns, it is also detected that western equatorial Pacific SST anomalies are positively correlated with the convergence of humidity transport flux and rainfall over the upper Madeira river basin. These results also suggest that warmer than usual western equatorial Pacific, negative TSA-SSA SST gradient, and particularly warm condition in SSA are related to intense rainfall and floods in south-western Amazon, as noticed in 2014.

5. Concluding remarks

Rainfall over the Madeira River basin was unprecedented during the 2013–14 wet season, in particular since mid-January 2014, and thus generating anomalously high river discharges during that season. Rainfall was about 80–100% above normal in the region. Comparing to the mean values for the 1970–2013 period, discharge in Porto Velho station was 74% higher and it was 380% in Rurrenabaque station, at the exit of the Andes, while rainfall in Bolivian Amazon and Brazilian western Amazon was more than 100% above normal. These events produced inundations and landslides, severely impacting cities of Bolivian, Peruvian and Brazilian Amazon.

While extreme floods in north-western and central Amazonia have been related to anomalies in the tropical Pacific and Atlantic (related to La Niña or to a southward migration of ITCZ due to the warmer than normal TSA SST), the 2014 flood in south-western Amazonia is characterized by warm condition in the western Pacific-Indian Ocean and with exceptional warm conditions in SSA SST. These features are associated to unprecedented rainfall and floods over the Madeira basin, particularly in the Andean countries (Bolivia and South of Peru) and over the western Brazilian Amazonia. Results from composite and correlation analysis suggest that TSA-SSA SST gradient is a main driver of humidity transport over south-western Amazon, and this became exceptionally intense during January 2014, when an anticyclonic anomaly established over most of subtropical South America east of the Andes, weakening the SACZ activity (linked to drought conditions in Southeastern Brazil during summer of 2014) and enhancing activity of the SALLJ with increased rainfall over western Amazonia-Southern Andes. Finally, our results would be useful to propose further observational analysis and numerical modelling experiment in order to test the ocean-atmosphere physical processes that are behind the flooding in upper Madeira basin.

Acknowledgments

We especially thank the Servicio Nacional de Meteorologia e Hidrologia (SENAMHI) of Bolivia and Peru, the Agencia/Autoridad Nacional de Aguas (ANA- Brazil and Peru), all the members of the Observatory for Environmental Research ORE-HYBAM (Geodynamical, hydrological and biogeochemical control of erosion/alteration and material transport in the Amazon basin) for providing discharge and rainfall data. Among them, special thanks to William Santini, Franck Timouk, Oscar Fuertes, Waldo Lavado and Pascal Fraizy. JCE and JR thank the Institute for Research and Development (IRD) for providing funds through the PPR-AMAZ program. Thanks to Hans Segura, Ricardo Zubieta (Instituto Geofísico del Perú—IGP) and Lucio Vergara (ANA-Peru) for their help in TRMM data processing. JM was funded by the Rede Clima, Brazilian National Institute of Science and Technology (INCT) for Climate Change funded by CNPq Grant Number 573797/2008-0, and FAPESP Go-Amazon Grant

Number 2013/50538-7. Finally, we thank both anonymous reviewers for their constructive suggestions, which substantially improved this work.

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