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Extreme flood events in the Bolivian Amazon wetlands

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ABSTRACT

Study region: The Amazonian wetlands of Bolivia, known as the Llanos de Moxos, are believed to play a crucial role in regulating the upper Madeira hydrological cycle, the most important southern tributary of the Amazon River. Because the area is vast and sparsely populated, the hydrological functioning of the wetlands is poorly known.
Study focus: We analyzed the hydrometeorological configurations that led to the major floods of 2007, 2008 and 2014. These data, together with flood mapping derived from remote sensing images, were used to understand the dynamics of the Llanos during the three flood events.
New hydrological insights for the region: The results showed that large floods are the result of the superimposition of flood waves from major sub-basins of the region. As a previous study suggested, the dynamics of the floods are controlled by an exogenous process, created by the flood wave originating in the Andes piedmont that travels through the Mamoré River; and by an endogenous process, which is the runoff originating in the Llanos. Our study showed that the first process is evident only at the initial phase of the floods, and although important for attenuating the rising flood wave, it is of lesser importance compared to the endogenous process. We conclude that the endogenous process controls the magnitude and duration of major floods.

1. Introduction

Amazonian wetlands play a crucial role at the watershed scale because they are important habitats that support biodiversity of the ecosystem (Junk, 1997) and because they modulate water fluxes, both their quality and quantity. Amazon wetlands affect the basin sediment load, modifying water and dissolved and particulate material fluxes from upland watersheds through river drainage networks (Dunne et al., 1998; Guyot et al., 1996; Junk and Worbes, 1997; Meade et al., 1985; Melack and Forsberg, 2001; Mertes et al., 1996). Water residence time in wetlands alters river discharge due to the exchange of water between river and floodplain, and it promotes large evaporative losses (Bonnet et al., 2008; Mertes et al., 1995; Rudorff et al., 2014). In addition, water residence time in Amazon wetlands is crucial in the regulation of biogeochemical and biotic processes (Bouchez et al., 2012; Junk et al., 1989; Viers et al., 2005) and consequently carbon dioxide (CO_2) and

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methane (CH_4) emissions (Abril et al., 2014; Kayranli et al., 2010; Melack et al., 2004; Richey et al., 2002). Both sediments and biogeochemical dynamics depend on the spatial and temporal patterns of hydrology, which, in addition to rainfall distribution, are also influenced by the topography, soil and vegetation (Mertes et al., 1995).

Over the period 2000–2014, the Amazon Basin has been affected by severe droughts (Espinoza et al., 2012; Marengo et al., 2008; Marengo et al., 2011; Tomasella et al., 2010) and floods (Marengo et al., 2012). The increased frequency of extremes in the Amazon has led Gloor et al. (2013) to suggest an intensification of the hydrological cycle starting from the 1990s, mainly concentrated in the wet season, which is responsible for "progressively greater differences in Amazon peak and minimum flows". It has been shown that these extreme events have the potential to cause serious disruptions in the ecological functioning of the "*terra firme*" Amazon forest ecosystems (e.g. Phillips et al., 2009) and alter the normal functioning of the wetlands, pushing the physiological adaptations and behavioral changes of living organisms beyond their resilience limits (Junk, 2013). In addition, they compromise the livelihoods of riverine communities, which are dependent on the flood pulses (Tomasella et al., 2013).

The Bolivian Amazon wetlands have also been affected by these extreme events. In terms of impacts and magnitude, the floods of 2007, 2008 and 2014 caused significant economic impacts and a large number of fatalities. According to CEPAL (2008), the floods of 2007 and 2008 caused losses of approximately $US 220 million in Bolivia, with approximately 250,000 affected people and 49 fatalities. The major flood of 2014 left 340,000 people affected, 64 fatalities, and 49,000 km^2 of crops lost. The losses in the livestock sector in the Beni Department reached $US 111 million with 350,000 people affected (Fundación-Milenio, 2014)

Sea surface temperature anomalies (SSTA) are believed to be influencing extreme flood events in the Bolivian Amazon (Ronchail et al., 2005; Ronchail et al., 2003). Higher than normal rainfall in the region has been related to a weak meridional sea surface temperature gradient (Ronchail et al., 2005). For this reason, the floods of 2007 and 2008 have been associated with El Niño and La Niña events, respectively (CEPAL, 2008), although the atmospheric processes associated with these extremes remain undocumented. The unprecedented rainfall over the Madeira Basin during the rainy season of 2013–2014, on the other hand, was related to warm conditions in the Pacific-Indian and sub-tropical south Atlantic, and exceptional warm conditions in the Atlantic Ocean, which favored the humidity transport over South western Amazonia (Espinoza et al., 2014). These features induced an anti-cyclonic anomaly over subtropical South America during January 2014, which enhanced rainfall over the Madeira Basin drainage area (Espinoza et al., 2014).

One of the major Amazonian wetlands is the "Llanos de Moxos", located between the Andes and the Brazilian shield, in the Southwest Amazon Basin within Bolivia. Like other wetlands in Amazonia, the "Llanos", because of its size and remoteness, is poorly monitored and therefore not well understood. To overcome this limitation, passive and active remote sensing techniques are crucial because they can provide information with the spatial and temporal resolution required in many studies. Passive systems have been used to characterize Amazonian wetlands in terms of vegetation, fluvial dynamics, limnology, geomorphology and flood extension despite their limitations due to interference from cloud coverage and vegetation (e.g. Alcantara et al., 2008; Arraut et al., 2013; de Lucia Lobo et al., 2012; Hamilton et al., 2002; Plotzki et al., 2012; Rudorff et al., 2009). Complementary, active systems (mainly Synthetic Aperture Radar—SAR) have proven to be extremely useful for mapping flood extension, vegetation, water stages and storage (e.g., Alsdorf et al., 2007; Arnesen et al., 2013; Hess et al., 2003; Martinez and Le Toan, 2007)

Moreover, remote sensing when combined with hydro-meteorological data makes it possible to understand the hydrological function of wetlands (Da Silva et al., 2010; Da Silva et al., 2012; Frappart et al., 2006). In this context, most of the existing knowledge of the flood dynamics in the "Llanos de Moxos" is based on the use of remote sensing and observational data (Bourrel et al., 2009; Hamilton et al., 2002; Hamilton et al., 2004) and more recently with the use of hydrological models (Paiva et al., 2013; Siqueira et al., 2015).

In this study, we have analyzed the hydrometeorological context of the 2007, 2008 and 2014 floods in the upper Madeira Basin and the dynamics of the Bolivian wetlands during those major floods events. We critically assess the temporal and spatial hydrological patterns that explain the magnitude and duration of those floods, both in the main rivers and wetlands. To achieve these goals, we have integrated hydrological and rainfall data from several sources in Bolivia, Brazil and Peru. Considering that the study region is vast and isolated, we complemented the scarce hydrometeorological data with multi-temporal flood maps based on the use of nouvelle remote sensing techniques. This study brings new insights to previous studies regarding the influences of extreme climatic conditions in the region, and it is a contribution to reducing the gap between common perception and scientific evidence regarding the floods in the region.

2. Wetlands of the Bolivian Amazon

The Bolivian wetlands, "Llanos de Moxos", is a vast savanna floodplain of approximately 150,000 km^2 (Hamilton et al., 2004) located in the Mamoré–Beni–Guaporé (Iténez) rivers fluvial system, between the eastern Andes, the adjacent Amazon alluvial fans and the Precambrian Brazilian shield (Fig. 1). The mean altitude at the "Llanos" is approximately 150 m with a mean slope less than 10 cm per km (Guyot, 1993). The natural vegetation is mixed: grassland and savannah vegetation in seasonally flooded areas, and evergreen tropical forests in non-flooded areas, although deforestation has converted part of the forest areas to pasture (Hamilton et al., 2004).

The hydrological dynamics of the "Llanos" is controlled by four major sub-basins (Fig. 1): the Guaporé (Iténez), the Mamoré, the Beni and the Madre de Dios, which define the upper Madeira River Basin, the main southern tributary of the