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Tree-ring based reconstruction of Río Bermejo streamflow in subtropical South America

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SUMMARY

Precipitation on the subtropical Andes in northwestern Argentina is the main source of freshwater to rivers, which provide water for consumption, hydroelectric generation and irrigation of agricultural fields. Regional streamflow records for the past 60 years indicate a period of enhanced inter-annual and inter-decadal variability during recent decades. Here we present a long-term perspective of streamflow variations for Río Bermejo, a major river in the subtropics of Argentina–Bolivia. This streamflow reconstruction covers the period 1680–2001 and was performed using principal component regression models based on precipitation sensitive tree-ring width series. Composite tree-ring chronologies from *Juglans australis*, *Cedrela lilloi* and *Schinopsis lorentzii* were used as predictors to reconstruct the May–October (dry season) streamflow variations. Monthly instrumental streamflow records were used to assess the temporal relationship between climatic data and tree-ring records. The regression model explains 52% of the variance of May–October Bermejo discharge (R^2 *adj* = 0.499) over the period 1941–1992. Analyses of the frequency, intensity and duration of pluvials and droughts indicates a sustained increase in streamflow since the 1960s, which is exceptional since 1680. Pearson's correlation coefficients between Río Bermejo records against gridded interpolated precipitation and outgoing longwave radiation indicate that the South American monsoon is the main source of regional precipitation and the consequent discharge of subtropical rivers in northern Argentina. Long-term streamflow reconstructions in subtropical South America contribute to our understanding of past and present climate variations and the related large-scale atmospheric features that drive these variations.

1. Introduction

Water scarcity is a major constraint for the socio-economic development of a region. Water shortages severely impact food production, electric power generation and access to clean drinking water (Arnell et al., 2001; Viviroli et al., 2003). Hence, the management of water resources requires a comprehensive view of their natural variability over multiple time scales (Woodhouse and Lukas, 2006). Long-term records are vital to provide reliable patterns of runoff variability from interannual to decadal and longer scales. However, in tropical and subtropical South America long and high quality meteorological and hydrological records are rare and few records exceed 50 years in length. Although these gauge records are used for planning and engineering design of irrigation and hydropower infrastructures, they are too short to determine the true discharge variability, particularly the severity and duration of high (pluvial) and low flow (drought) periods in subtropical South America.

Water resources from mountainous regions are vital to natural ecosystems and human activities in the adjacent lowlands. This is particularly the case in arid and semiarid regions of the world, where water from mountains contributes between 50% and 90% of total streamflow (Messerli et al., 2004). Detailed assessments of the main hydrological patterns and factors affecting mountain hydrology conditions are still limited in many regions, despite the importance of mountains as sources of freshwater (Masiokas et al., 2013). Río Bermejo basin covers over 123,000 km^2 in the

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tropical and subtropical sectors of southern Bolivia and northwestern Argentina. Starting from the high Andes in northwest Argentina and southwest Bolivia, Río Bermejo flows eastwards over 1,300 km to contribute to the Paraguay-Paraná river system (Rafaelli et al., 2001). Total basin population is estimated as ca. 1.3 million (COBINABE, 2010), of which 39% is located in semi-urban/rural sectors (small cities, rural farmers and indigenous communities) (Manzanal and Arrieta, 2000). Livestock breeding, which is an important source of income for rural populations, is mainly concentrated in flood pasture lands where cattle are reared wildly, taking advantage of natural watering places during the dry season.

Sediment concentrations in Río Bermejo average 8 kg/m^3, amongst the highest in the world and the river discharges ca. 100 million tons/year to Río Paraguay. Although Río Bermejo contributes only 2% of total discharge it provides almost 50% of the total suspended solid material delivered to Río de la Plata (Pedrozo and Bonetto, 1987; Brea and Spalletti, 2010), the second largest river in South America after the Amazon. Most of the suspended sediment originates from erosion of unconsolidated deposits during the rainy season in the basins of Río Iruya and Río Grande (upper Río Bermejo basin; Rafaelli et al., 2001). As a result of the large amount of sediment transport, the river periodically changes its course in the lower and flatter sectors of the basin. Consequently, this dynamic behavior has hampered the effective use of water for irrigation in the lower part of the basin. Argentina and Bolivia established a Binational Commission (COBINABE, Comisión Binacional de los ríos Bermejo y Grande de Tarija) for the sustainable natural resource management in both watersheds. In 1995, this Binational Commission requested assistance from the World Bank, through the Global Environmental Facility (FMAM/GEF) to develop a water resource management program for the Río Bermejo-Grande de Tarija basins. The GEF assistance proposed a Strategic Action Program that could solve the trans-boundary environmental problems affecting the basins. Clearing of forests for cultivation and widespread overgrazing has accelerated biodiversity loss, erosion, water scarcity, floods and other environmental hazards (Gasparri et al., 2013). Forest loss and cattle ranching also aggravate sediment mobilization contributing to downstream environmental degradation and reducing the quality of life and cultural resources of native population (OAS, 2005). Moreover, a drier or longer dry season also places considerable stress on communities without access to reliable municipal or groundwater sources (Anchukaitis et al., 2014). In this context, a better understanding of Río Bermejo interannual fluctuations is critical to assess streamflow variability at different temporal scales (Woodhouse and Lukas, 2006; Urrutia et al., 2011).

Tree rings provide annually-resolved records which can be used as proxy for reconstructing long-term variability in regional hydroclimate (Meko and Woodhouse, 2011). Tree growth is influenced by the same climatic variables that modulate runoff, particularly precipitation and evapotranspiration. Therefore annual or seasonal variations in discharge may be reconstructed from tree rings based on the strong relationship between tree-growth and river discharge. A number of tree-ring based streamflow reconstructions has been developed for North America (see Meko and Woodhouse, 2011 and references therein). However, only seven reconstructions have been developed in South America, four in Chile (Lara et al., 2008; Urrutia et al., 2011; Muñoz, 2012; Lara et al., 2014) and three in Argentina (Holmes et al., 1979; Cobos and Boninsegna, 1983; Mundo et al. 2012). In Argentina, the first streamflow reconstruction was developed by Holmes et al. (1979) who extended the Río Limay and Río Neuquén records back to 1601 using *Araucaria araucana* and *Austrocedrus chilensis* tree-ring chronologies from northern Patagonia. Cobos and Boninsegna (1983) used *Austrocedrus* tree rings from central Chile to reconstruct the streamflow for the Atuel River in Argentina back to 1576. Recently, Mundo et al. (2012) updated and extended the reconstruction of Río Neuquén over the period 1346–2000.

Tree-ring based reconstructions of hydrological and climatic variations in tropical and subtropical regions of South America are rare, reflecting the paucity of tree-ring chronologies in these regions. In tropical South America, temporal variation in the Amazon River discharge has been inferred from a single chronology of *Piranhea trifoliata* growing in seasonally-flooded plains (Schöngart et al., 2004). In the subtropics, Flamenco et al. (2011) developed a preliminary flow reconstruction of Río San Francisco, a tributary of Río Bermejo utilizing artificial neural network structures drawn from two ring-width chronologies (*Juglans australis* and *Cedrela lilloi*).

In this study we develop a multi-century tree-ring based reconstruction for Río Bermejo streamflow using a nested multiple regression approach (Meko, 1997; Cook et al., 2002). This is the first statistically validated hydrological reconstruction for the subtropics and uses a network of subtropical chronologies in nortwestern Argentina. We also identify the dominant oscillatory modes in the Río Bermejo streamflow reconstruction and their relationships with regional and continental atmospheric circulation.

2. Study area

2.1. Regional climate

The South America Summer Monsoon (SASM) is induced by low-latitude temperature differences between the continent and the oceans and modulates the atmospheric circulation over tropical-subtropical South America in summer (IPCC, 2007; Garreaud et al., 2009). The onset of the wet season in central and southeastern Amazonia typically occurs between the end of September and early October and by late November deep convection covers most of the central South America from the equator to 20°S. During the mature phase of SASM between late November and late February, the area of main convective activity is centered over tropical central South America and connects with a convection band of cloudiness and precipitation extending from southern Amazonia toward southeastern Brazil and the adjacent Atlantic Ocean (Vera et al., 2006). This diagonal band of precipitation maxima over the ocean is known as the South Atlantic Convergence Zone (SACZ). The SACZ is evident year round but more intense during summer, producing episodes of intense rainfall over much of southeastern South America. At intraseasonal timescales, the SACZ is part of a seesaw pattern of precipitation over eastern South America. Periods of enhanced precipitation over the SACZ are accompanied by decreased rainfall in subtropical plains of northern Argentina, Paraguay and Uruguay, including the Río Bermejo basin. Opposite, roughly symmetric conditions prevail during weak SACZ periods. As a regional response to the strong convective heating over the Amazon, an upper-level high-pressure cell, called the Bolivian High, is formed. At low levels, a deep continental low is formed over the Chaco region (the Chaco Low). The interaction between circulation associated with the Chaco Low and the Andes reinforces the transport of moisture from tropical to subtropical South America. The regional intensification of the air circulation east of the Andes is due to the South American Low-Level Jet (SALLJ) which transports considerable moisture between the Amazon and La Plata basin over the subtropical plains as far as 35°S (Paegle and Mo, 2002; Saulo et al., 2004). In northwestern Argentina, humid air masses moving from northeastern to southwestern collide with the mountain ranges, forcing the air to rise and cool generating abundant orographic precipitation.