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Reconstructing streamflow variation of the Baker River from tree-rings in Northern Patagonia since 1765

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SUMMARY

The understanding of the long-term variation of large rivers streamflow with a high economic and social relevance is necessary in order to improve the planning and management of water resources in different regions of the world. The Baker River has the highest mean discharge of those draining both slopes of the Andes South of 20°S and it is among the six rivers with the highest mean streamflow in the Pacific domain of South America (1100 $m^3\ s^{-1}$ at its outlet). It drains an international basin of 29,000 km^2 shared by Chile and Argentina and has a high ecologic and economic value including conservation, tourism, recreational fishing, and projected hydropower. This study reconstructs the austral summer – early fall (January–April) streamflow for the Baker River from *Nothofagus pumilio* tree-rings for the period 1765–2004. Summer streamflow represents 45.2% of the annual discharge. The regression model for the period (1961–2004) explains 54% of the variance of the Baker River streamflow ($R^2_{adj} = 0.54$). The most significant temporal pattern in the record is the sustained decline since the 1980s ($\tau = -0.633$, $p = 1.0144 * 10^{-5}$ for the 1985–2004 period), which is unprecedented since 1765. The Correlation of the Baker streamflow with the November–April observed Southern Annular Mode (SAM) is significant (1961–2004, $r = -0.55$, $p < 0.001$). The Baker record is also correlated with the available SAM tree-ring reconstruction based on other species when both series are filtered with a 25-year spline and detrended (1765–2004, $r = -0.41$, $p < 0.01$), emphasizing SAM as the main climatic forcing of the Baker streamflow. Three of the five summers with the highest streamflow in the entire reconstructed record occurred after the 1950s (1977, 1958 and 1959). The causes of this high streamflow events are not yet clear and cannot be associated with the reported recent increase in the frequency of glacial-lake outburst floods (GLOFs). The decreasing trend in the observed and reconstructed streamflow of the Baker River documented here for the 1980–2004 period is consistent with precipitation decrease associated with the SAM. Conversely, other studies have reported an increase of summer streamflow for a portion of the Baker River for the 1994–2008 period, explained by ice melt associated with temperature increase and glacier retreat and thinning.

Future research should consider the development of new tree-ring reconstructions to increase the geographic range and to cover the last 1000 or more years using long-lived species (e.g. *Fitzroya cupressoides* and *Pilgerodendron uviferum*). Expanding the network and quality of instrumental weather, streamflow and other monitoring stations as well as the study and modeling of the complex hydrological processes in the Baker basin are necessary. This should be the basis for planning, policy design and decision making regarding water resources in the Baker basin.

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1. Introduction

Water availability is a main limitation to future economic and social development in the different regions of the planet (Arnell et al., 2001; Viviroli et al., 2003). Changes in water availability due to climatic fluctuations as well as to an increase in water demand has raised the interest in understanding the susceptibility of agriculture, industry, hydroelectricity and domestic use to these variations (Meko and Woodhouse, 2011). This situation applies even to areas of relatively high annual rainfall, such as Northern Patagonia (40° – 48°S) in Chile under a rainy temperate climate (Dussaillant et al., 2012; Lara et al., 2003).

Instrumental precipitation and streamflow records in Chile located between 37° and 46°S show a dominant decreasing trend since the 1950s (Pezoa, 2003; Rubio-Álvarez and McPhee, 2010), and this area has experienced an estimated 30% precipitation decrease for the 1900–1999 period (Intergovernmental Panel on Climate Change, 2001). Regional climate models predict that this trend will continue in the region as well as in central Chile, especially during the austral summer (December–February, DGF, 2007). Limitations in water availability have been intensified by an increase in water demand in recent decades (Lara et al., 2003). These trends stress the importance of understanding the long-term variability of precipitation and streamflow, beyond the available instrumental records that in most cases start in 1950 and have limited quality, as well as geographic and elevation coverage (Dussaillant et al., 2012; Rubio-Álvarez and McPhee, 2010).

Tree-ring records provide continuous, annually-resolved series of past environmental changes for the last several centuries and in some cases, millennia. Long reconstructions can be developed by correlating tree-growth records with discharge and their variability may be analyzed at several frequencies. Reconstructions of streamflow from tree rings have been extensively used in North America to document and understand long-term trends in water availability (e.g. Brito-Castillo et al., 2003; Jain et al., 2002; Meko et al., 2007; Woodhouse, 2001; Woodhouse and Lukas, 2006). However, few streamflow reconstructions have been developed in South America, three of them in Argentina, for the Atuel River in Mendoza and for the Limay and Neuquén Rivers (Cobos and Boninsegna, 1983; Holmes et al., 1979; Mundo et al., 2012). In Chile two tree-ring streamflow reconstructions have been recently developed. One for the Puelo River (41° 35′S) and the other one for the Maule River (35° 40′S), both covering the last 400 years. (Lara et al., 2008; Urrutia et al., 2011). These reconstructions have improved the understanding of streamflow temporal and spatial patterns and their climatic forcings along the north–south hydroclimate gradient in the Pacific domain of Southern South America from Mediterranean-type to rainy temperate climates. Therefore, it is necessary to expand the latitudinal range of streamflow reconstructions, in order to enhance the knowledge of long-term discharge variability in Southern South America.

The understanding of the long-term variation of large rivers streamflow with a high economic and social relevance is necessary in order to improve the planning and management of water resources in different regions of the world. The Baker River has the highest mean discharge of those draining both slopes of the Andes South of 20°S and it is among the five rivers with the highest mean streamflow in the Pacific domain of South America (recorded mean annual streamflow 945 $m^3 s^{-1}$ at the Baker at the junction with Ñadis River gauge station and estimated at 1100 $m^3 s^{-1}$ at its outlet, Dussaillant et al., 2012).

Four other rivers draining to the Pacific that have a higher mean streamflow than the Baker are located in Colombia and one in Ecuador (Montaño and Sanfeliu, 2008; Sánchez et al., 2010). The Baker River drains a basin of 29,000 km^2 shared by Chile and Argentina. Both countries signed a Treaty on the Environment that includes the Protocol on Shared Water Resources. This protocol is oriented to cooperate and coordinate activities towards the protection, conservation and sustainable use of hydrological resources through the concept of integrated watershed management according to General Plans of Water Use for specific watersheds. Nevertheless, the Protocol does not establish compulsory or mandatory actions to any of its parts and it does not include conflict resolution procedures or obligations (Pardo, 2008). The Baker River is internationally known due to its high ecologic and economic value including conservation, tourism, recreational fishing, and projected hydropower from possible construction of 2 dams for the generation of 1020 Mw/h. The future of this project is uncertain due to the social conflict that it has raised, involving several international organizations and broad public attention (Dussaillant et al., 2012; Vince, 2009).

The main objective of this study was to develop a tree-ring reconstruction of the Baker River streamflow, expanding the short available instrumental records starting in 1961. The second objective was to understand the long-term temporal variability of the Baker River discharge from the interannual to the multi-decadal scales. The third objective was to identify the main large-scale atmospheric circulation and climatic forcings influencing river discharge of this southern river compared to the ones already analyzed in Southern South America.

2. Methods

2.1. Study area

The Baker River drains an international basin located between 46° and 48°S, that covers 29,286 km^2, mainly in Chile. It also includes 9013 km^2 in Argentina (30.8% of the basin (Fig. 1). The western portion of the watershed is formed by the Northern Patagonian Ice Field (NPIF). The North and North eastern portion of the basin is characterized by Lake General Carrera or Buenos Aires (local names in Chile and Argentina, respectively), that covers an area of 1850 km^2, being the second largest lake in South America. The main land use land cover types in the Baker basin determined from the GIS data provided by CONAF et al. (1999) are shrublands and grasslands (42% of the total), native forests (19% of the total, almost all forests located in Chile), barren lands located above-treeline (14%), (NPIF) and associated glaciers (3.1%).

The watershed flows towards the South-West and the outlet is in Bajo Pisagua at the Baker Fjord (Fig. 1). The main tributaries to the Baker (all of which have mean flows at least one order of magnitude smaller than the main stem) are the Nef, Colonia and Ventisqueros coming from the NPIF on the western side, and Chacabuco, Cochrane, Del Salto and Ñadis draining from the East (Dussaillant et al., 2012). Glacial-lake outburst floods (GLOFs) occur in the Colonia valley and have started to be studied in recent years. An increase in the occurrence of GLOF events has been reported. Several occurred in 2008 and 2009 (fall, spring and summer) and caused rapid floods constituting important hazards in the Baker valley (Dussaillant et al., 2009).

The geology of the Baker basin is dominated by the metamorphic rocks of upper Paleozoic age, as well as by different volcanic pyroclastic materials (Pino, 1976). Pleistocene glacial dynamics has driven most of the geomorphologic evolution of the Baker basin which has been overprinted by fluvial dynamics, landslides and volcanism due to Hudson volcano activity during the Holocene. The inner terminal moraine system of Lake General Carrera, was dated between 23 and 16 ky BP and therefore they can be associated with the Last Glacial Maximum (Kaplan et al., 2004).