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Long-term glacier variations in the Central Andes of Argentina and Chile, inferred from historical records and tree-ring reconstructed precipitation

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ABSTRACT

Snow and ice in the Central Andes of Chile and Argentina (33–36 °S) are the major source of water for the highly populated regions near the cities of Santiago and Mendoza. However, our knowledge of the forces driving the general glacier retreat in the region is limited. In order to obtain a long-term perspective of glacier fluctuations and their relationships with climate in the Central Andes, historical glacier variations were documented and compared with a tree-ring precipitation reconstruction based upon *Austrocedrus chilensis* trees. A multi-proxy approach (historical documents, old aerial photographs and satellite imagery) was used to map the fluctuations of eight glaciers, including the Cipreses Glacier, which provides the oldest record of glacier variations in the region starting in AD 1842. All the studied glaciers exhibited a negative trend during the 20th century with mean frontal retreats between −50 and −9 m y^{-1}, thinning rates between 0.76 and 0.56 m y^{-1} and a mean ice area reduction of 3% since 1955. More than 350 tree-ring cores were combined into three tree-ring chronologies, which strongly correlate with the instrumental precipitation in Santiago de Chile (33°26′ S; 70°41′ W, 520 m asl). Based on these records, a 712-year precipitation reconstruction was developed. This reconstruction is characterised by a centennial oscillation indicating marked dry conditions around the years 1440 and 1600 AD. Wet conditions were prevalent in the years 1500, 1650 and particularly around 1850 AD. Since this precipitation maximum, the reconstruction shows a clear, secular, decreasing trend. The reduction in precipitation indicated by this reconstruction for the last 150 yr, in combination with a significant warming recorded in Central Chile, are the main causes of the observed current glacier retreats.

1. Introduction

Due to its transitional location between subtropical and temperate latitudes, the climate in Central Chile is characterised by a high inter-annual variability in precipitation (Aceituno et al., 1993; Montecinos and Aceituno, 2003; Quintana, 2004). At the end of 1960s and during the 1990s, this region experienced extreme drought events (Quintana, 2000), which seriously affected water consumption, irrigation, and generation of hydroelectric power (Norero and Bonilla, 1999). These natural restrictions in water supply occurred concurrently with higher human pressure on water resources, generating strong competition for water allocation as a result of the regional economic growth (Rosegrant et al., 2000). The drought events in this region are partially correlated to cold phases of ENSO, the so-called La Niña events (Masiokas et al., 2006), which are typically associated with negative glacier mass balances, as opposed to positive glacier mass balances during El Niño events (Escobar and Aceituno, 1998).

Water consumption in this region of Argentina and Chile is highly dependent on snow accumulation and glacial melt, particularly during summers preceded by episodic winter droughts when up to 67% of the water flow of Río Maipo (Peña and Nazarala, 1987) and 70% of the discharge of Río San Juan (Leiva, 1999) has been generated by glacial meltwater. In this regard, and additionally due to recent glacier retreat and wasting ice, runoff from some glaciated Chilean basins has increased (Carrasco et al., 2005). In the long-term, runoff is expected to drop significantly during the dry seasons due to the disappearance of glaciers, in similar fashion to what is currently occurring in the Tropical Andes (Juen et al., 2007).

In spite of the general trend of glacial retreat on both sides of the Andes during the 20th century (Llorens and Leiva, 1995; Leiva, 1999; Rivera et al., 2002), some glaciers experienced sudden advances. This occurred both in Chile during the 1950s (Lliboutry, 1956) and in Argentina during the 1930s, and 1980s, when Glaciar Grande del Nevado del Plomo advanced rapidly, damming a valley and generating two floods (Bruce et al., 1987). Similarly, Glaciar de la Laguna in Río Atuel advanced 1400 m between 1970 and 1982 (Cobos and Boninsegna, 1983). Some of these advances have been related to

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Table 1
Geographical description of studied glaciers.

	Chile				Argentina			
River basin	Cachapoal			Tinguiririca	Atuel			
Glacier name	Cipreses	Cortaderal	Palomo	Universidad	De la Laguna	Humo	Corto	Fiero
Latitude S	34°33'21"	34°38'32"	34°33'12"	34°42'51"	34°31'21"	34°33'59"	34°35'00"	34°36'32"
Longitude W	70°22'10"	70°15'35"	70°16'05"	70°20'53"	70°06'24"	70°07'56"	70°08'20"	70°09'19"
Length (km)*	10.6	9	7.3	10.6	5.2	3.5	3.2	5.4
Total area (km^2)*	35.7	15	14.5	29.2	8.2	10.7	2.2	7.8
General aspect	W	SE	NE	S	S	SE	E	SE
Min. elevation (m)**	2616	2738	2629	2463	3250	3060	3136	2903
Max. elevation (m)**	4365	4845	4478	4543	4338	4089	3945	4014

*Area and length based upon a Landsat ETM+ acquired on January 20, 2000.
** Altitude extracted from SRTM data.

surge events (Leiva, 1999), which are not necessarily responses to climatic changes. In this situation they may be generated by changes in the normal subglacial drainage system, particularly when temperate glaciers are involved, such as in Central Chile and Argentina (Paterson, 1994; Harrison and Post, 2003).

Recent glacial responses in this part of the Andes have previously been related (Rivera et al., 2002) to both atmospheric warming (Rosenblüth et al., 1997) and decreases in precipitation (Quintana, 2004). As yet, little research has been done regarding Holocene glacial responses (e.g., Espizúa, 1993). These long-term variations are useful for understanding how water resources may change in the future as a consequence of predicted temperature and precipitation changes (e. g., IPCC, 2001).

In order to obtain a better insight into the long-term climate variability of this part of the Andes, two independent proxies were used: historical documents on glacier variations and precipitation variability reconstructed by moisture-sensitive tree-ring chronologies. These two proxies allow extension of analysis into the past, for periods where instrumental records are limited or non existent (Bradley et al., 2004).

For this purpose, eight glaciers located in the Cachapoal and Tinguiririca basins in Chile, and the Atuel basin in Argentina were selected (Table 1, Figs. 1 and 2). Most of these glaciers have previously been analysed (e.g., Caviedes, 1979; Cobos and Boninsegna, 1983; Rivera et al., 2006), allowing the reconstruction of long-term variations of frontal glacier tongues. One of the glaciers with the longest historical record of frontal variations is Glaciar Cipreses (34°33′ S; 70°22′ W), whose frontal position was first noted by Domeyko in 1842 (Domeyko, 1978). More recent aerial photographs and satellite images (Table 2) have enabled updating of glacier positions to the year 2007.

Glaciar Cipreses was also chosen for more detailed analysis, due to disjunctive stands of *Austrocedrus chilensis* at lower altitudes in its valley (Ciprés de la Cordillera, Fig. 2). This species has previously been used to provide a proxy record for precipitation in central Chile (Boninsegna, 1988, 1992; Luckman and Villalba, 2001). A robust moisture-sensitive tree-ring network was developed to analyse the long-term precipitation variability during the last seven centuries. This annually-resolved proxy allowed the determination of the leading modes of precipitation variability at different time scales

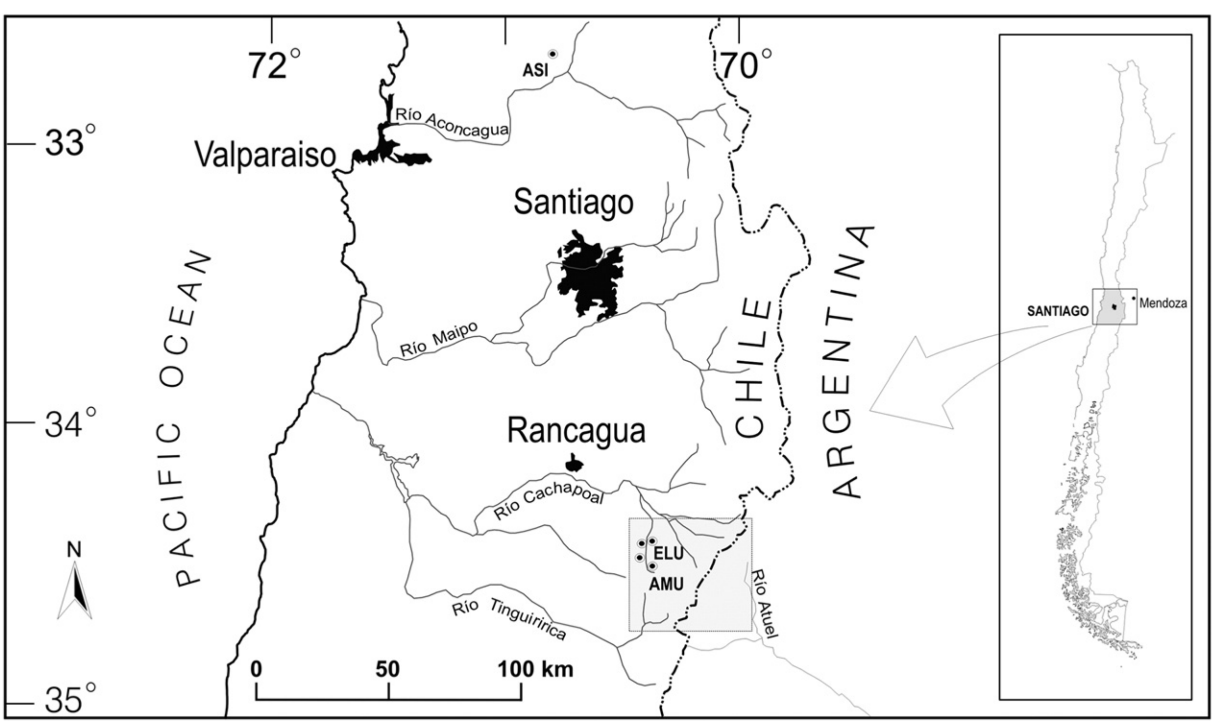

Fig. 1. Map of Central Chile and Argentina showing the study area, main rivers, cities and the *Austrocedrus chilensis* tree-ring sites. Locations of tree-ring chronologies are indicated by black points: ASI, El Asiento in the Río Aconcagua area, and ELU and AMU along the Río Cipreses. The box corresponds to the area covered by the Landsat ETM+ image shown in Fig. 4.