



Relationships between climate variability and radial growth of *Nothofagus pumilio* near altitudinal treeline in the Andes of northern Patagonia, Chile



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ABSTRACT

Global warming is expected to enhance radial tree growth at alpine treeline sites worldwide. We developed a well-replicated tree-ring chronology from *Nothofagus pumilio* near treeline in a high precipitation climate on Choshuenco Volcano (40°S) in Chile to examine: (a) variation in tree radial growth in relation to interannual climatic variability; and (b) relationships of radial growth to variability in El Niño Southern Oscillation (ENSO) and the Antarctic Oscillation (AAO) at interannual and decadal time scales. A tree-ring chronology based on 99 tree-ring series from 80 *N. pumilio* trees near treeline showed a high series intercorrelation (0.48) indicating a strong common environmental signal. Radial growth is negatively correlated with precipitation in late spring (November–December). Temperature and tree growth are positively correlated during late spring and early summer (November–January). Interannual variability in both seasonal climate and in tree growth is strongly teleconnected to ENSO and AAO variability. Radial growth of *N. pumilio* in this humid high-elevation forest does not show a positive trend over the past half century as predicted from global treeline theory and broadscale warming in the Patagonian–Andean region. Instead, tree growth increased sharply from the 1960s to a peak in the early 1980s but subsequently declined for c. 30 years to its lowest level in >100 years. The shift to higher radial growth after c. 1976 coincides with a shift towards warmer sea surface temperatures in the tropical Pacific which in turn are associated with warmer growing season temperatures. The decline in tree growth since the mid-1990s is coincident with the increasingly positive phase of the AAO and high spring precipitation periods associated with El Niño conditions. The recent shift towards reduced growth of *N. pumilio* at this humid high-elevation site coincident with rising AAO mirrors the reduced tree growth beginning in the 1960s for trees growing in relatively xeric, lower elevation sites throughout the Patagonian–Andean region. The current study indicates that *N. pumilio* growth response in humid high-elevation environments to recent broad-scale warming has been non-linear, and that AAO and ENSO are key climatic forcings of tree growth variability.

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1. Introduction

High elevation treelines are believed to be physiologically controlled by low temperatures implying that these ecotones should be highly responsive to global warming (Körner, 1998; Körner and

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Paulsen, 2004; Hoch and Korner, 2005). Recent research has shown that the *Nothofagus pumilio* treeline in the Patagonian–Andean mid-latitudes of South America is located at an isotherm of 6.6 °C for the growing season which matches the global pattern for most alpine treeline sites (Fajardo and Piper, 2014). For the Patagonian–Andean region centered on 42.5°S latitude, coarse scale (5° latitude) analyses of instrumental climate records indicate an increase of annual and growing season (October–March) mean temperature during 1901–2010 on the order of 1 °C (Veblen et al., 2011; Ji et al., 2014). Furthermore, tree-ring climate reconstructions in the northern Patagonian–Andean region (37°–46°S) show an increase of 0.53 °C

in mean annual temperature for the 20th century when compared with the mean over the 1640–1899 period (Villalba et al., 2003). Thus, according to conventional explanations of alpine treeline (e.g. Körner, 1998), one would predict increased tree growth near treeline in the Patagonian Andes under recent and continued warming. Although the treeline ecotone is widely considered to be a sensor of climate variability and an excellent environment to test the possible effects of global warming (Körner, 1999; Malanson et al., 2011), relatively few treeline studies have been conducted in the temperate latitudes of the southern hemisphere (Cuevas, 2000; Harsch et al., 2009).

In the Andes of northern Patagonia, large scale tropical and high latitude climate forcings modulate regional climate variability through teleconnections, and consequently should be reflected in tree growth patterns (Villalba, 2007; Villalba et al., 2012). The El Niño–Southern Oscillation (ENSO) and the Antarctic Oscillation (AAO; also known as the Southern Annular Mode, SAM) are the two main large scale climate forcings determining the regional climate of northern Patagonia, operating at different temporal scales and having distinct effects on local temperature and precipitation (Díaz and Markgraf, 2000; Villalba, 2007; Garreaud et al., 2009). These climate forcings influence regional climate variability, and therefore are expected to affect climate-sensitive ecological processes in the temperate forests of the Andes of Northern Patagonia. ENSO is the most widely investigated large scale driver, and is manifested as interannual (2–7 years) variability in sea surface temperatures in the tropical Pacific (Díaz and Markgraf, 2000). In Patagonian–Andean forests, ENSO variability has been shown to significantly affect radial tree growth (Villalba et al., 1997), tree seedling establishment in alpine treeline habitats (Daniels and Veblen, 2004), wildfire activity (Kitzberger and Veblen, 1997; Kitzberger et al., 1997; Veblen et al., 1999; Holz et al., 2012), and tree mortality events in forests and woodlands (Villalba and Veblen, 1998; Suarez et al., 2004).

The AAO is the most important extra-tropical climate forcing in the southern hemisphere. It is characterized by departures of opposite sign in atmospheric pressure at sea level over the Antarctic Continent and a circum-global band at 40°–50°S (Thompson et al., 2000; Miller et al., 2006; Garreaud et al., 2009). The persistent positive trend in the AAO since the 1950s has been associated with warmer and drier conditions over the northern Patagonian Andes (Aravena and Luckman, 2009; Garreaud et al., 2009). Inter-annual variability as well as the post-1950 positive trend in AAO have been shown to affect numerous ecological and hydrological processes in the Patagonian–Andean region, including radial tree growth (Christie et al., 2011; Villalba et al., 2012) and stream discharge in northern Patagonia (Lara et al., 2008; Urrutia et al., 2011; Mundo et al., 2012a), wildfire throughout Patagonia (Veblen et al., 1999; Holz and Veblen, 2011; Mundo et al., 2012b; Holz et al., 2012), rodent population dynamics in northern Patagonia (Murúa et al., 2003), and outbreaks of tree defoliating insects in *Nothofagus* forests in southern Patagonia (Paritsis and Veblen, 2011). However, there are no studies that address the potential effects of AAO variability on radial tree growth of high elevation trees on the humid western side of the Patagonian Andes.

According to conventional treeline control theory, broad-scale climate warming should favor upward advance of treeline and should enhance tree radial growth near altitudinal treeline (Körner, 1998; Körner and Paulsen, 2004; Hoch and Körner, 2005). Thus, in the current research we use dendrochronological methods to examine the potential effects of climate variability on tree growth of *N. pumilio* in a humid high elevation forest near treeline on Choshuenco Volcano (40°S), Chile (Fig. 1). Specific objectives are: (a) to examine the variation in tree radial growth in relation to inter-annual climate variability and determine relationships to monthly and seasonal temperature and precipitation variables, and (b) to

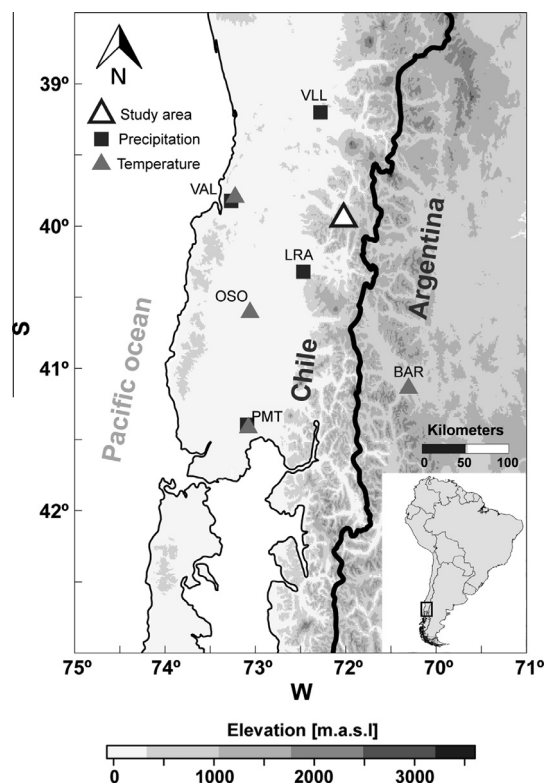


Fig. 1. (A) Location of the Choshuenco Volcano study area and weather stations of temperature and precipitation (for details see Table 1).

examine possible associations of variability of tree radial growth to variability in ENSO and the AAO at interannual and decadal time scales.

2. Material and methods

2.1. Study area

Data collection was conducted in January 2012 on the Chilean side of the Andes on the northwestern flanks of the Choshuenco Volcano at 39°53'S, 72°03'W near altitudinal treeline at elevations between 1350 to 1400 m above sea level (Fig. 1). In this section of the Andes, the summits of the Andean Cordillera generally reach altitudes between 2000 to 2700 m a.s.l. The climate in the study area is oceanic humid temperate with a mild Mediterranean-type influence. Precipitation origin is from the Pacific Ocean and is modulated by the westerly winds (Garreaud et al., 2009). The three nearest climate stations at elevations of 100, 210, and 845 m a.s.l. have mean annual of precipitation from 1946 to 2446 mm and mean annual temperatures ranging from 8.1 to 11.0 °C (Table 1). Precipitation is concentrated in April through August and during those months occurs mostly as snow above of 1000 m a.s.l. (Miller, 1976). Thus, moisture availability is least during the summer months of January through March. Within the century-long rise in growing season temperature since c. 1900 in the northern Patagonian–Andean region (40–45°S/70–75°W) temperatures temporarily cool during the 1960s and rise again after 1976 (Villalba et al., 2003; Veblen et al., 2011). Soils are andisols and have developed from parent material of volcanic ash (Hildebrand-Vogel et al., 1990), which under forests is marked by a black Ah-horizon rich in organic material. Soils are characterized by a high pore volume and high water infiltration rate. This structure results in soils with poor water retention capacity (Hildebrand-Vogel et al., 1990).

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