

RESEARCH ARTICLE

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Key Points:

- The 60 year long chronologies of cellulose $\delta^{18}\text{O}$ in two species are compared
- The isotopic climate signal recorded in *F. cupressoides* is relatively weak
- The $\delta^{18}\text{O}$ in *N. pumilio* is useful for reconstructing temperature over a large area

Supporting Information:

- Supporting Information S1

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Are the oxygen isotopic compositions of *Fitzroya cupressoides* and *Nothofagus pumilio* cellulose promising proxies for climate reconstructions in northern Patagonia?

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Abstract Tree ring $\delta^{18}\text{O}$ chronologies from two native species (*Fitzroya cupressoides* and *Nothofagus pumilio*) in northern Patagonia were developed to assess their potential for paleoclimate reconstructions. The five annually resolved cellulose $\delta^{18}\text{O}$ chronologies (two for *F. cupressoides* and three for *N. pumilio*) are located on the Andes along the steep west-to-east precipitation gradient. Over the common 60 years long interval, the five site- $\delta^{18}\text{O}_{\text{cell}}$ chronologies exhibit a strong common signal as indicated by the significant mean intercorrelation ($r = 0.61$, $p < 0.05$) and the high percentage (65%) of total variance explained by the first empirical orthogonal function. Although correlation analyses reveal that the two mean species- $\delta^{18}\text{O}_{\text{cell}}$ chronologies are mainly modulated by December–May temperature, the *N. pumilio* chronology shows a greater sensitivity to record temperature variations ($r = 0.57$, $p < 0.05$). The $\delta^{18}\text{O}_{\text{cell}}$ of *N. pumilio* contains a regional temperature signal representative of a large area in southern South America under the influence of the Southern Annular Mode. This study indicates that $\delta^{18}\text{O}_{\text{cell}}$ in *N. pumilio* is a promising proxy to reconstruct past variations in temperature in South America south of 38°S.

1. Introduction

Recent increase in global mean temperature concurrent with major changes in the world's hydrological cycle [Intergovernmental Panel on Climate Change (IPCC) et al., 2013] strengthen the need to estimate anthropogenic climate changes in addition to natural climate variability. While climate variability and forcing mechanisms in the Northern Hemisphere are quite well understood [e.g., Andersen et al., 2004; Selten et al., 2004; Mann et al., 2008; Frank et al., 2010; Allen et al., 2012; Hoell et al., 2014], the Southern Hemisphere (SH) is poorly documented and underrepresented in global climate reconstructions [Neukom et al., 2010; Ahmed et al., 2013; IPCC et al., 2013]. In this context, South America is a key region for examining past climate changes in the SH.

The Andes Cordillera is the most important mountain range in the SH and crosses the South American continent from the northern tropics in Colombia (10°N) to the southern tip of the continent (55°S). The Patagonian Andes act as an impressive topographic barrier to the persistent Westerlies winds, which brings to the continent moisture from the South Pacific Ocean, leading to one of the most dramatic west-to-east precipitation gradient on Earth [Smith and Evans, 2007]. The variability of the extratropical western South America climate (i.e., interannual and interdecadal changes) is mostly driven by the interactions, through atmospheric teleconnections, between the circum-Antarctic cyclonic belt (reflected by changes in the Southern Annular Mode, SAM) and the subtropical Pacific high-pressure cell, which in turn is affected by changes in the El Niño–Southern Oscillation. The interactions between these large-scale tropical and high-latitude climate forcings influence the latitudinal distribution of rainfall and the temperature patterns from the subtropics to subantarctica latitudes [Gillett et al., 2006; Archer and Caldeira, 2008; Garreaud et al., 2008]. Their large spatial and long-term temporal variability are poorly documented over the last millennia [Villalba, 2007]. Therefore, the acquisition of paleoclimate data in Patagonia may improve the representation of the SH in global climatic reconstructions.

Paleoenvironmental information recorded in natural archives can be extracted through a combination of traditional and more advanced techniques [Bradley, 1999]. Paleoproxies allow reconstruction of past climates beyond the limit of instrumental records and thus help the interpretation of recent and ongoing climate

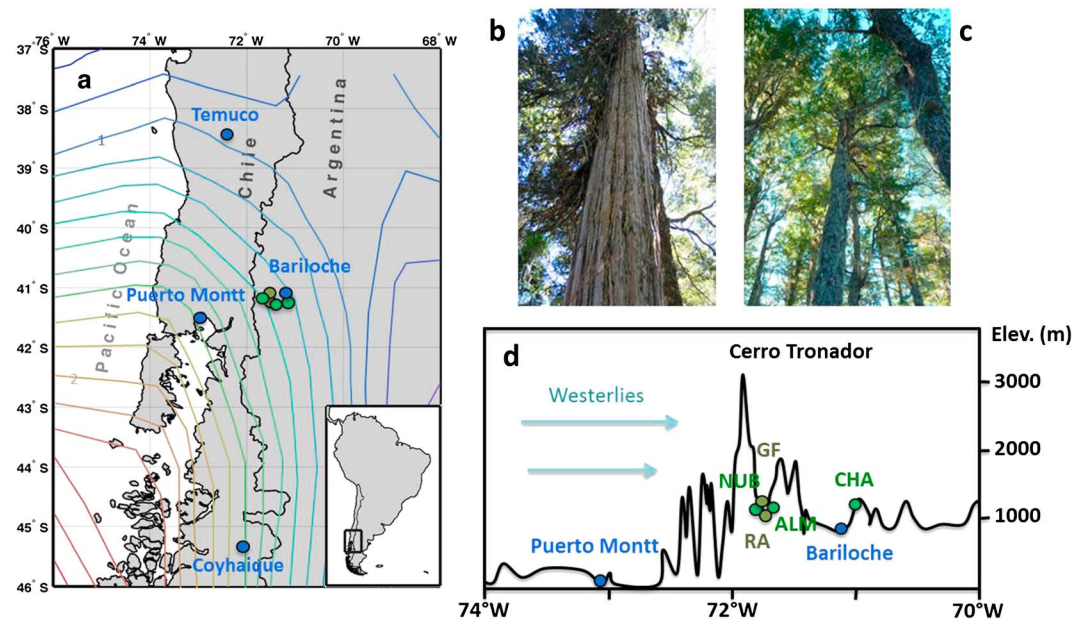


Figure 1. (a) Location map of the $\delta^{18}\text{O}_p$ precipitation stations from GNP network (Temuco, Bariloche, Puerto Montt, and Coyhaique) and the tree ring sampling sites. Long-term mean (over 1979–2000) of summer precipitation (December–January–February) are plotted as contour lines (in mm/d). (b) *F. cupressoides* and (c) *N. pumilio* trees. (d) Elevation along a west-east transection at 41°S (adapted from Villalba *et al.* [2003]) and location of tree ring sites (green circles) and meteorological stations (blue circles). Sampling sites are Glaciar Frías (GF) and Río Alerce (RA) for *F. cupressoides* (pale green) and Paso de las Nubes (NUB), La Almohadilla (ALM), and Challhuaco (CHA) for *N. pumilio* (light green). The pale blue arrows indicate the main direction of the Westerlies winds.

change. Tree rings provide continuous and annually resolved paleoclimatic records that may extend from several centuries to millennia [e.g., Jones *et al.*, 2009; Corona *et al.*, 2010; Yang *et al.*, 2014]. Variations in the width and density of annual rings have been widely applied as proxy estimates of past climatic conditions, such as air temperature and precipitation [e.g., Fritts, 1976; Lara *et al.*, 2008; Barichivich *et al.*, 2009; D'Arrigo *et al.*, 2012]. In the Andes Mountain of southern Chile and Argentina, tree rings have been used to reconstruct a wide variety of climatic variables at different spatial scales [see Villalba *et al.*, 1997; Lara *et al.*, 2005; Boninsegna *et al.*, 2009; Muñoz *et al.*, 2014]. In particular, the long-lived and slow-growing endemic *Fitzroya cupressoides* and the dominant deciduous *Nothofagus pumilio* in subantarctic forests have been used for temperature reconstructions [Villalba, 1990; Lara and Villalba, 1993, 1994; Lara *et al.*, 2001, 2005; Aravena *et al.*, 2002; Villalba *et al.*, 2009]. The temporal longevity of *F. cupressoides* [Lara and Villalba, 1993] and the vast geographical distribution of *N. pumilio* [Veblen, 1979; Schlatter, 1994], not only along the north-south temperature but also the west-to-east precipitation gradients, make these species valuable archives of past climate variations. However, due to the environmental complexity introduced by the Andes, tree growth may be influenced by different physical, biological, and climatic factors making tree ring width (TRW) and density difficult to be interpreted. The potential of tree ring oxygen isotopes for high-resolution climatic reconstruction has largely been demonstrated [e.g., Gessler *et al.*, 2014; Hartl-Meier *et al.*, 2014; Labuhn *et al.*, 2014; Porter *et al.*, 2014]. Climatic responses indicate, in some cases, a stronger sensitivity to climate of the isotopic signatures than the TRW [McCarroll and Loader, 2004; Daux *et al.*, 2011; Gessler *et al.*, 2014]. The oxygen isotopic composition of cellulose ($\delta^{18}\text{O}_{\text{cell}}$) records the $\delta^{18}\text{O}$ of the source water derived from the precipitation, which itself is related to the temperature variations at middle and high latitudes. It is modulated by the evaporation in the ground and evaporative/diffusion processes in the leaf, which are largely controlled by vapor pressure deficit [e.g., Barbour *et al.*, 2005; Gessler *et al.*, 2013].

There is a lack of tree ring $\delta^{18}\text{O}$ studies in South America; only one annually resolved chronology of tree ring $\delta^{18}\text{O}$ from *Austrocedrus chilensis* has been carried out in the northern Patagonian Andes [Roig *et al.*, 2006]. The strong correlation between this 100 year long series and the Southern Oscillation Index (SOI), a measure of the development and intensity of El Niño/La Niña events in the Pacific Ocean, is promising and encourages the continuation of $\delta^{18}\text{O}$ -based climate reconstructions in Patagonia.

Table 1. Location of the Tree Ring Sites and Statistics on the Respective $\delta^{18}\text{O}_{\text{cell}}$ Chronologies^a

Site	Abbreviation	Lat.	Long.	Alt. (m)	Mean	SD	AC1
<i>Fitzroya Cupressoides</i>							
Glaciar Frías	GF	41°08'S	71°48'W	950	29.1	0.47	0.11
Río Alerce	RA	41°11'S	71°46'W	1060	29.2	0.67	0.29
<i>Nothofagus Pumilio</i>							
Paso de las Nubes	NUB	41°09'S	71°48'W	1274	30.4	0.71	0.11
La Almohadilla	ALM	41°11'S	71°47'W	1425	29.7	0.76	0.15
Challhuaco	CHA	41°15'S	71°17'W	1612	30.1	0.63	0.04

^aSite: Site abbreviation used in the study: GF: Glaciar Frías, RA: Río Alerce, NUB: Paso de las nubes, ALM: La Almohadilla, and CHA: Challhuaco; Lat.: latitude, Lon.: longitude, Alt.: altitude, Mean: mean value, SD: standard deviation, and AC1: lag 1 autocorrelation of the site- $\delta^{18}\text{O}_{\text{cell}}$ chronologies.

Here we tested the performance of the oxygen isotopic composition of the cellulose of *F. cupressoides* and *N. pumilio* for recording climate variability. For this purpose, we developed annually resolved $\delta^{18}\text{O}_{\text{cell}}$ chronologies from five high-elevation forest sites in northern Patagonia (41°S) for the last 60 years (1952–2011), conduct interspecies comparisons of the oxygen isotope signals, and explore the links between these isotopic records and the climate of the region.

2. Materials and Methods

2.1. Sample Preparation and Isotopic Analyses of Cellulose

Tree ring samples were collected during the austral summer of 2013 at five sites in northern Patagonia, Argentina (Figure 1). Two sites of *F. cupressoides* and three sites of *N. pumilio*, growing at elevations of 950–1050 and 1270–1610 m above sea level, were selected along the regional precipitation gradient from Cerro Tronador (41°09'S, 71°53'W) to the drier Challhuaco Valley near Bariloche (41°05'S, 71°21'W, Figure 1 and Table 1). The sampling sites were located on moderate to steep slopes (approximately 15° to 40°) for both species. The soils were therefore very likely well drained. Paired increment cores were extracted from more than 30 trees growing in similar growth conditions (competition and microsite conditions), at breast height (1.3 m above the ground), using a Pressler borer with a diameter of 5 mm. The core samples were dated to the calendar year of their formation and crossdated following the techniques described by Stokes and Smiley [1968]. Since the biological growth season in the Southern Hemisphere overlaps two calendar years (from September to May), rings were assigned to the year when ring growth began [Schulman, 1956]; therefore, the last complete ring in the cores sampled in summer 2013 was 2011 (the 2012 ring was still incomplete at the time of the sampling). The *N. pumilio* trees analyzed here are part of a ring width data set which has been used by Lavergne *et al.* [2015] to evidence the change with time of the effect of climate on tree ring growth.

At least four trees per site are usually considered a minimum sample for completing a representative reconstruction of environmental variability from the isotopic composition of tree ring cellulose [Leavitt and Long, 1984; Robertson *et al.*, 1997; Treydte *et al.*, 2001, 2006; Leavitt, 2010]. Here we selected six trees from each of the five sites, according to the following criteria: (1) their ring widths were wide enough to conduct isotopic measurements; (2) the trees sampled were older than 150 years so that their 60 outlying rings were not affected by juvenile effects, and (3) their ring widths chronology was highly correlated with the site chronology. Since *N. pumilio* has diffuse pores and *F. cupressoides* very narrow rings, early and late woods could not be separated and whole rings were cut instead. For each species, we selected 12 years distributed throughout the last 60 year period for examining the intertree $\delta^{18}\text{O}$ variability. The years were selected so as to cover a variety of ring widths. The $\delta^{18}\text{O}_{\text{cell}}$ from the six individual trees of each test set shows good reproducibility (average pairwise correlation coefficient of 0.7 and 0.53 for *N. pumilio* and *F. cupressoides*, respectively; Table 2). Reflecting this coherence, an Expressed Population Signal [Briffa, 1984; Wigley *et al.*, 1984] superior to 0.85 and a confidence interval around the mean inferior to 0.5% were obtained for four and six trees, respectively for *N. pumilio* and *F. cupressoides*. Except for the two test sets, at each site, 60 year long (1952–2011), annually resolved isotope chronologies (site- $\delta^{18}\text{O}_{\text{cell}}$ hereafter) were produced by pooling dated growth rings from trees prior to the isotopic analyses.

Table 2. Pearson's Correlation Coefficients Among the Site- and Species- $\delta^{18}\text{O}_{\text{cell}}$ Chronologies and the Leading EOF Over the 1952–2011 Period^a

Site	RA	NUB	ALM	CHA	EOF1	<i>F. Cup.</i>
GF	0.72	0.38	0.48	0.49	0.75	
RA		0.52	0.60	0.45	0.82	
NUB			0.71	0.52	0.78	
ALM				0.70	0.88	
CHA					0.79	
<i>N. pum.</i>						0.61

^aSite abbreviations as in Table 1. *N. pum.*: *N. pumilio* species- $\delta^{18}\text{O}_{\text{cell}}$ chronology and *F. cup.*: *F. cupressoides* species- $\delta^{18}\text{O}_{\text{cell}}$ chronology. Correlations are significant at $p < 0.05$.

The wood samples were chipped and then grounded in a ball mill for homogenization. α -cellulose was extracted from the wood according to the SOXHLET chemical method derived from *Leavitt and Danzer* [1993]. α -cellulose was homogenized ultrasonically with a sonotrode apparatus and freeze-dried. Cellulose samples of around 0.20 mg were loaded in silver foil capsules. The $\delta^{18}\text{O}_{\text{cell}}$ was determined with a high-temperature

conversion elemental analyzer (Thermo Scientific) coupled with a Finnigan MAT252 mass spectrometer (at Laboratoire des Sciences du Climat et de l'Environnement) according to the procedure described in *Shi et al.* [2011]. An internal laboratory reference of cellulose (Whatmann® CC31) was used to correct for instrument drift and to normalize the data to internationally accepted standards. Along the sequence analyses, the isotopic composition of CC31 was measured every three samples. The standard deviation (SD) obtained from the measurement of the isotopic composition of 10 consecutive CC31 standards was typically $\pm 0.25\%$. The analysis of oxygen isotopes of each sample was repeated at least once and up to three times. This methodology allows rejecting outlier measurements, which do not fit with the maximum accepted range.

2.2. Correlations and Calibrations

The first empirical orthogonal functions (EOF1) were extracted from the five site- $\delta^{18}\text{O}_{\text{cell}}$ chronologies. For each species, the site- $\delta^{18}\text{O}_{\text{cell}}$ chronologies are well intercorrelated ($0.52 < r < 0.72$, $p < 0.05$; Table 2); therefore, we constructed two species- $\delta^{18}\text{O}_{\text{cell}}$ chronologies of 12 trees each by averaging the specific site chronologies. Temperature and precipitation controls on $\delta^{18}\text{O}_{\text{cell}}$ variability were empirically identified using simple and partial correlations (Seascorr MATLAB routine [*Meko et al.*, 2011]) of the species- $\delta^{18}\text{O}_{\text{cell}}$ chronologies and leading EOF with monthly temperature and precipitation from Bariloche (nearest meteorological station at $41^{\circ}12'S$ – $71^{\circ}12'W$, 840 m above sea level; Servicio Meteorológico Nacional, Figure 1). The station records were homogenized and gap filled using the R routine HOMER (HOMogenization softwarE in R [*Mestre et al.*, 2013; *Venema et al.*, 2013]) and climatic series from additional stations located in the area (40° – $43^{\circ}S$ and 71° – $73^{\circ}W$).

The use of partial correlation allows assessing the relationship between two variables while controlling for the effects of a third variable. In northern Patagonia, temperature is negatively correlated with precipitation in summer (December–March; $r = -0.57$, $p < 0.01$; 1931–2009). Therefore, we performed partial correlations between species- $\delta^{18}\text{O}_{\text{cell}}$ chronologies and precipitation while controlling for temperature. Calculations were conducted over the whole growing season from September to May. The significance of each correlation was evaluated using bootstrapping with 1000 Monte Carlo simulations [*Ebisuzaki*, 1997].

On the basis of these correlations, we conducted split periods of calibration-verification tests with half of the climatic time series (identified as potential climatic target) for calibration and the other half for assessing the

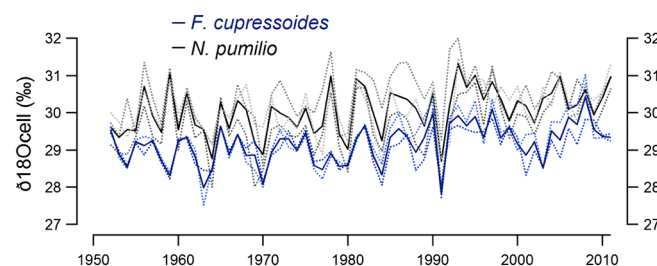


Figure 2. The two 60 year species- $\delta^{18}\text{O}_{\text{cell}}$ time series (in ‰ versus SMOW). The five site- $\delta^{18}\text{O}_{\text{cell}}$ chronologies are shown in dashed lines.

quality of the reconstruction (verification). To assess the predictive skill of the model, the coefficient of determination (r^2) of the regression models, reduction of error statistic (RE) [*Fritts*, 1976], coefficient of efficiency (CE) [*Cook et al.*, 1994], and the Durbin-Watson statistic (DW) [*Durbin and Watson*, 1971] were systematically compared for independent calibration

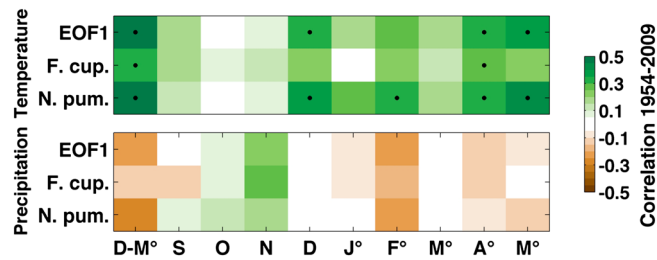


Figure 3. Correlation of the species- $\delta^{18}\text{O}_{\text{cell}}$ chronologies and leading EOF with monthly temperature and precipitation from Bariloche station for the period 1954–2009. Correlations are given for a 9 month window from September, at the start of the growing season, to May of the following year (°) corresponding to the end of the growing season. The correlation coefficients of the $\delta^{18}\text{O}_{\text{cell}}$ series with the December–May mean temperature and total precipitation are also shown (D-M°). The stippling points indicate months with significant correlations ($p < 0.05$).

and verification periods [Zang and Biondi, 2015]. The coefficient of determination (r^2) indicates the extent to which the two series covary but is insensitive to any offset in the absolute values. The RE and CE are measures of shared variance between target and proxy series. They compare the fit between measured and reconstructed values (root-mean-square error, RMSE) with the fit obtained by simply using the calibration mean (RE) or verification mean (CE) of the actual data. Positive values for these two tests indicate predictive skill of the regression model. The DW tests for first-order autocorrelations in the model residuals. A DW value of around 2 indicates no first-order autocorrelation in the residuals, whereas a value of DW substantially different from 2 suggests autocorrelation [Durbin and Watson, 1971].

3. Results

3.1. Interspecies Coherence of $\delta^{18}\text{O}_{\text{cell}}$

The means (and standard deviations) of the species- $\delta^{18}\text{O}_{\text{cell}}$ chronologies are $29.14 \pm 0.57\text{‰}$ and $30.06 \pm 0.61\text{‰}$ for *F. cupressoides* and *N. pumilio*, respectively ($N = 60$ in both cases; Table 1). The serial correlations range from 0.04 to 0.29, indicating almost no lag effects in these records. The difference of 0.92‰ between the two species- $\delta^{18}\text{O}_{\text{cell}}$ chronologies is not statistically significant (Student’s t test: $t = 8.64$, $p < 0.01$).

The species- $\delta^{18}\text{O}_{\text{cell}}$ time series are highly correlated with one another ($r = 0.61$, $p < 0.01$; Table 2). This is in accordance with the leading EOF of the five site- $\delta^{18}\text{O}_{\text{cell}}$ chronologies, accounting for 65% of the total

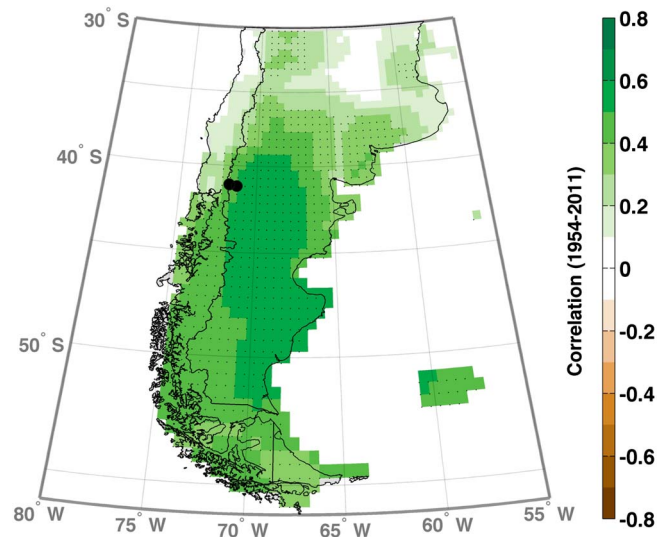


Figure 4. Correlation field across southern South America between December and May temperature (CRUTS 3.2 data set [Harris et al., 2014]) and the *N. pumilio* $\delta^{18}\text{O}_{\text{cell}}$ chronology for the period 1954–2011. The stippling points indicate grid points with significant correlations ($p < 0.05$). The black points situate the sampling sites.

Table 3. Calibration and Verification Statistics of *N. pumilio* $\delta^{18}\text{O}_{\text{cell}}$ Against December–May Temperature Using Simple Linear Regression^a

Calibration				Verification				
Period	r^2	RMSE	DW	Period	RMSE	r^2	RE	CE
1954–1982	0.26	0.77	2.08	1983–2010	0.42	0.33	0.26	0.67
1983–2010	0.33	0.50	1.68	1954–1982	0.69	0.26	0.33	0.51

^a r^2 : Squared correlation coefficient, RE: reduction of error statistic, CE: coefficient of efficiency, DW: Durbin-Watson statistic, and RMSE: root-mean-square error of the estimate for two independent periods. Overall period (1954–2010): $r^2 = 0.35$; DW = 1.58, and RMSE = 0.58 representing 11% of the range of December–May temperature.

variance, and thus indicating strong spatial interspecies coherency. The species- $\delta^{18}\text{O}_{\text{cell}}$ time series both show a progressive increase of approximately 0.9‰ from the 1960s to the mid-1990s and a relative leveling off during the last decades (since 1990–2000; Figure 2). Remarkably, a feature shared by the two series is the approximately –2‰ drop in 1991.

3.2. Climatic Signals Recorded in Tree Ring $\delta^{18}\text{O}$

The correlations of the two species- $\delta^{18}\text{O}_{\text{cell}}$ chronologies tend to be positive with temperature and negative with precipitation. For *F. cupressoides*, only the correlation with April temperature is significant ($r = 0.26$, $p < 0.05$; Figure 3). For *N. pumilio*, the correlations with temperature over December–May are significant ($r = 0.32$ to 0.43 , $p < 0.05$). Correlations of the two species- $\delta^{18}\text{O}_{\text{cell}}$ chronologies with monthly precipitation are not significant at 95% (Figure 3). The leading EOF is significantly and positively correlated to temperature ($r = 0.29$ to 0.40 ; $p < 0.05$) over the same months as *N. pumilio*, and thus, it mainly captures the $\delta^{18}\text{O}_{\text{cell}}$ signal of the *N. pumilio* trees.

Significant relationships between the isotopic chronologies and the mean of December to May temperatures confirm the primary influence of temperature on $\delta^{18}\text{O}_{\text{cell}}$ variations in the two species ($r = 0.30$ and $r = 0.57$ for *F. cupressoides* and *N. pumilio*, respectively, $p < 0.05$; Figure 3). The $\delta^{18}\text{O}_{\text{cell}}$ in *N. pumilio* captures more strongly the mean temperature variations. Consistently, the leading EOF of the site- $\delta^{18}\text{O}$ chronologies significantly correlates with the mean temperature over the period December–May ($r = 0.50$, $p < 0.05$).

To assess the spatial representativeness of the temperature signal recorded in the species- $\delta^{18}\text{O}_{\text{cell}}$ chronologies, we conducted a spatial correlation analysis between these time series and gridded temperature records from the CRUTS 3.2 data set [Harris et al., 2014] averaged over December–May in the area 30°S–56°S and 55°W–80°W. The highest correlations for *N. pumilio* appear near the sampling sites, but significant correlations are also observed all across southern South America from 35°S to 55°S (Figure 4). Similar, but weaker, spatial correlations are observed for *F. cupressoides* (Figure S1 in the supporting information). These results indicate that the regional *N. pumilio* $\delta^{18}\text{O}_{\text{cell}}$ chronology (and to a lesser extent the *F. cupressoides* chronology) accurately records mean temperature variations over a large area across Patagonia.

3.3. Calibration of Tree Ring $\delta^{18}\text{O}$ on Temperature

The final goal of this study is the reconstruction of climate in southern South America during the past centuries. Here we explore the robustness of the $\delta^{18}\text{O}_{\text{cell}}$ -based reconstruction of climate using the oxygen isotopic composition of the cellulose in *N. pumilio* tree rings as a proxy for December–May temperature. Split-period

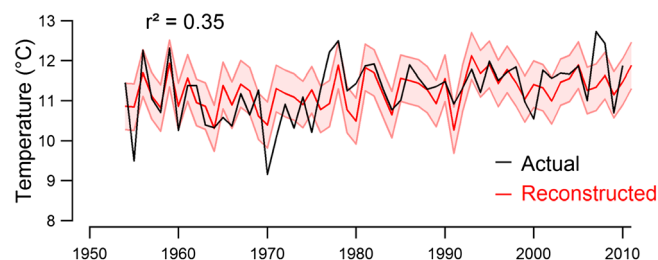


Figure 5. Actual and reconstructed December–May mean temperatures with the *N. pumilio* $\delta^{18}\text{O}_{\text{cell}}$ mean chronology for the period 1954–2011. The pink color band around the reconstruction indicates the root-mean-square error (RMSE = $\pm 0.58^\circ\text{C}$). The explained variance (r^2) is indicated.

verifications of the calibrated relationships (Table 3) indicate that the linear regression model (over 1954–2010) is reliable and has high predictive skills ($RE > 0$ and $CE > 0$). A DW statistic of around 1.58 for the linear model, whatever the calibration period considered, suggests only minimal residual autocorrelation. We therefore calibrated the mean December–May temperature over the whole period. Our linear regression model accounts for 35% of the actual temperature variance for the period 1954–2010, with a RMSE of 0.58°C, representing 11% of its variability range (Figure 5). For comparison, the predictive skills of the *F. cupressoides* calibration model were lower than for *N. pumilio* ($r^2 = 0.09$, $DW = 1.71$, and $RMSE = 0.69^\circ\text{C}$; Table S1 in the supporting information).

4. Discussion

In the following paragraphs, we address the performance of the $\delta^{18}\text{O}_{\text{cell}}$ of *F. cupressoides* and *N. pumilio* as climatic proxies for long-term paleoclimate reconstructions.

4.1. What Are the Physical Mechanisms Relating $\delta^{18}\text{O}_{\text{cell}}$ and Temperature?

Variations in regional temperature appear to modulate the $\delta^{18}\text{O}_{\text{cell}}$ fluctuations, particularly in *N. pumilio*. At midlatitudes, atmospheric temperature determines to a certain extent the atmospheric vapor condensation and the associated oxygen isotopic fractionation in the meteoric water. As a result, the $\delta^{18}\text{O}$ of the condensate precipitation (rain and snow) (hereafter $\delta^{18}\text{O}_p$) decrease with decreasing atmospheric temperature [Dansgaard, 1964]. There are few GNIP (Global Network of Isotopes in Precipitation) stations in southern South America (Figure 1), and most records are discontinuous and short. At the GNIP stations closest to the study sites (Puerto Mont and Bariloche), monthly values of $\delta^{18}\text{O}_p$ and mean temperatures are significantly correlated (Figure S2b in the supporting information), in line with earlier findings relating temperature to $\delta^{18}\text{O}_p$ in South America south of 40°S [Rozanski and Araguás-Araguás, 1995]. Moreover, over the continuous $\delta^{18}\text{O}_p$ record from 1989 to 2009 at Puerto Mont, the increasing trend of 0.8‰ is concomitant with a 0.7°C increase in temperature (Figure S2c in the supporting information). Considering that rain is the main source of water for trees, the positive trend of about 0.9‰ (from 1960–1970 to 1990–2000) in the two species- $\delta^{18}\text{O}_{\text{cell}}$ chronologies may indirectly reflect the increasing trend in temperature via the $\delta^{18}\text{O}$ of the source water (hereafter $\delta^{18}\text{O}_{\text{SW}}$), which itself is derived from $\delta^{18}\text{O}_p$.

In addition, soil and plant evaporation can profoundly modify the isotopic precipitation signal. Warm temperatures can indeed generate higher evaporation leading to enriched superficial soil water and/or enriched leaf water, possibly inducing enriched $\delta^{18}\text{O}_{\text{cell}}$ in tree rings [e.g., Gessler *et al.*, 2014]. Moreover, the equilibrium biochemical fractionation (ϵ_{bio}) associated with the imprinting of oxygen isotope signal in cellulose is dependent on temperature below 20°C [Sternberg and Ellsworth, 2011]. At Bariloche, the temperature of the growing season (December–May) averaged over 1952–2011 is $11.25 \pm 0.75^\circ\text{C}$. Applying the equation derived by Sternberg and Ellsworth [2011] yields $\epsilon_{\text{bio}} = 28.52 \pm 0.26\text{‰}$. As shown by the low value of the standard deviation, ϵ_{bio} is very stable over this 60 year long period. Therefore, the positive trend observed in the $\delta^{18}\text{O}_{\text{cell}}$ chronologies cannot be ascribed to the variations of this parameter. In other words, the relationship between temperature and $\delta^{18}\text{O}_{\text{cell}}$ may be inferred from the dependence on temperature (1) of $\delta^{18}\text{O}_p$ and (2) of the evaporative enrichment, but information is lacking to specify the relative contributions of these possible causes.

The abrupt decrease of approximately 2‰ in 1991 observed in the cellulose of the two species is very likely related to the temperature drop and the precipitation increase, which were reported in the southern sector of South America following the Pinatubo eruption of 15 June 1991 in Luzon (Philippines) [Rosenbluth *et al.*, 1997; Trenberth and Dai, 2007]. At Bariloche, the December–May drop in temperature associated with the Pinatubo eruption was about 1°C (compared to previous and following years). The second lowest $\delta^{18}\text{O}_{\text{cell}}$ in the *F. cupressoides* chronology is also coincident with the Agung eruption in 1963–1964 in Bali (Indonesia).

4.2. Which Species Is the Most Appropriate for Climate Reconstruction?

Despite the overall consistency between the two species, the climate signal recorded in *F. cupressoides* $\delta^{18}\text{O}_{\text{cell}}$ is weaker than in *N. pumilio*. Dendroclimatological studies conducted in Patagonia have reported negative relationships between the TRW of *F. cupressoides* and temperatures during the previous growing season [Villalba, 1990; Lara and Villalba, 1993, 1994; Neira and Lara, 2000], and a high degree of temporal autocorrelation in the TRW chronologies [Villalba, 1990]. This growth dependence on previous year climatic

conditions is related to starch reserves developed in previous summer. Starch reserves are less abundant if warm and dry conditions during the growing season limit carbon assimilation through the reduction of stomatal aperture [Deslauriers *et al.*, 2014; Urrutia-Jalabert *et al.*, 2015]. The simultaneous use of starch reserve and current photoassimilates, in different proportions from one year to the next, may lead to an ambiguous $\delta^{18}\text{O}_{\text{cell}}$ signal in *F. cupressoides*, poorly related to current year temperature. However, the lack of autocorrelation in the $\delta^{18}\text{O}_{\text{cell}}$ series from *F. cupressoides* indicates no substantial carryover effects due to remobilized reserves from previous summer. Further work is needed to understand *F. cupressoides* physiology and to examine the long-term carbon turnover of stored carbohydrates and its use for growth. *F. cupressoides* is one of the longest-lived tree in the world with a maximum life span over 3600 years [Lara and Villalba, 1993]. Therefore, these records could be very valuable archives if we were able to better understand the variations of the isotopic composition of its cellulose.

4.3. Is There Strong Local- to Large-Scale Climate Variability Recorded in $\delta^{18}\text{O}_{\text{cell}}$?

Spatial correlation fields between gridded December–May temperature and *N. pumilio*- $\delta^{18}\text{O}_{\text{cell}}$ shows a homogenous pattern over a large area south of ca. 38°S. Temperature in this extended region is mainly influenced by variations in the SAM. Indeed, in Patagonia, the strength of the Westerlies winds, which controls the variations of precipitation [Garreaud *et al.*, 2007, 2008, 2013] and influences atmospheric temperature, particularly in summer [Gupta and England, 2006; Garreaud *et al.*, 2013], is mainly modulated by the SAM [Thompson *et al.*, 2000; Marshall, 2003; Garreaud *et al.*, 2008]. The *N. pumilio*- $\delta^{18}\text{O}_{\text{cell}}$ chronology exhibits a significant positive correlation with the December–May SAM index ($r = 0.43$, $p < 0.05$; 1957–2010 [Marshall, 2003]). This correlation is quite strong, but weaker than the relation reported with temperature ($r = 0.57$, $p < 0.05$). We have shown that temperature controls directly and/or indirectly the oxygen isotopic composition of *N. pumilio* cellulose. However, as temperature is likely not the only controlling factor on $\delta^{18}\text{O}_{\text{cell}}$, and conditioned by different regional (in particular cloud cover) and local effects in addition to SAM, the link between $\delta^{18}\text{O}_{\text{cell}}$ and SAM is expected to be weaker. As a result the performance of the $\delta^{18}\text{O}_{\text{cell}}$ -based reconstruction of SAM is poorer than the temperature reconstruction (RE = 0.186, DW = 1.652, and RMSE = 0.92, representing 18% of the SAM variability from December to May).

The dominant climatic signal recorded in the $\delta^{18}\text{O}_{\text{cell}}$ of *N. pumilio* and *F. cupressoides* differs from the *A. chilensis* $\delta^{18}\text{O}$, located 5° north of our study area [Roig *et al.*, 2006]. Indeed, *A. chilensis* $\delta^{18}\text{O}$ was shown to record past variations in the summer SOI, which is the main mode of climate variability at the northwest corner of Patagonia (approximately 36°S [Montecinos and Aceituno, 2003]). Even if the links between the mode of climate variability and the isotopic compositions of tree rings are not straightforward, the latter contain relevant information on the former. Thus, our results encourage the development of multicentennial $\delta^{18}\text{O}_{\text{cell}}$ chronologies.

5. Conclusions

A reliable paleoclimate reconstruction based on tree ring proxies requires a comprehensive understanding of the factors influencing their variability. This study represents the first to investigate the potential of the oxygen isotopic composition of the cellulose in *F. cupressoides* and *N. pumilio* in northern Patagonia. Given its longevity (above 3600 years), the long-lived *F. cupressoides* is comparatively the most interesting species for long-term climate reconstructions in this area. Presently, our poor understanding of its complex physiology makes it difficult to determine the climatic signal recorded in its $\delta^{18}\text{O}_{\text{cell}}$. Our results indicate that *N. pumilio* represents a more robust paleoclimate archive. We show that $\delta^{18}\text{O}_{\text{cell}}$ of *N. pumilio* is consistent between sites, strongly related to variations in December–May temperature, and to a lesser extent to hemispheric forcings such as SAM. $\delta^{18}\text{O}_{\text{cell}}$ -based reconstructions would be representative of temperature variations over large areas of southern South America influenced by SAM. South of 38°S, *N. pumilio* is shown to be a good candidate for reconstructing not only local and regional temperature but also SAM variations. Analyses of a 200 year long $\delta^{18}\text{O}_{\text{cell}}$ chronology are currently in progress.

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