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Dendroclimatological reconstructions in South America: A review

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ABSTRACT

Recent years have seen a consolidation and expansion of tree-ring sample collection across South America. Most collections are concentrated in the temperate forests along the eastern and western slopes of the Southern Andes (32°S to 55°S). However, important advances in the reconnaissance and collection of new woody species useful for dendrochronology have recently been documented in new regions. The development of chronologies in tropical and subtropical arid regions of the Cordillera, and in particular the Bolivian Altiplano, is probably one of the most important recent advances in South American dendrochronology. *Polylepis tarapacana*, growing at 4000–4500 m elevation on the Altiplano, has yielded more than ten chronologies spanning the past 700 years. These records are highly correlated with summer variations in climate. The development of chronologies in the humid subtropics and tropics remains a major challenge. The number of tree-ring chronologies built up using species from these regions (ca. 40) is comparatively low in relation to the extent of tropical forests. The recognition of strong climate signals in tree rings from *Cedrela* species provides a unique opportunity to develop a tree-ring network in subtropical and tropical South America. The future of dendroclimatology in South American tropical regions is perceived as extremely promising.

Reconstructions of temperature, rainfall, streamflow, snow and regional atmospheric circulation based on ring width, density and stable isotopes, have been conducted using tree-ring chronologies from subtropical and temperate forests. These chronologies have also been used in studies relating South American tree rings to high-resolution proxies from other continents, and studies analyzing past changes in atmospheric circulation. The comparison of climatic reconstructions based on tree rings with projected atmospheric circulation patterns provides a useful bridge between past and future trends in global climate change, and its implications for human welfare and socio-economic development. Some examples of this bridging are presented in this review.

Future research should continue the development of long tree-ring chronologies to improve detection of decadal to centennial climatic variations and to distinguish between natural and human-induced climatic changes in South America. Efforts to develop new tree-ring chronologies in the tropical lowlands should also be encouraged. Collaboration among South American countries in training young scholars is crucial to maintain and increase the progress of dendroclimatology in the region. Initiatives facilitating the interaction between scientists from the Americas and overseas, such as done by the IAI and PAGES projects, should be broadened and their long-term continuation assured.

1. Introduction

Tree rings are the most numerous and widely distributed high-resolution climate archives in South America. During the past 40 years, more than 300 tree-ring chronologies have been developed along the Andes from the subtropical inter-mountain valleys to the cold environments at the southern tip of the continent. In addition, recent

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collections in tropical regions have shown the potential to extend the geographical coverage of tree-ring records to lower latitudes. Although comparatively lower in number, tree-ring records in South America presently provide the longest chronology for the Southern Hemisphere and the highest elevation records worldwide. In addition, the scarcity of instrumental records in South America makes the proxy-based climatic reconstructions highly valuable, and gives additional merit to the current network of tree-ring records across the continent.

South America is the only inhabited continent with land-mass south of 45°S. Forested mountains from 35° to 55°S intercept the westerly circulation, a major feature of the atmospheric circulation in the Southern Hemisphere. As a consequence, the tree-ring chronologies from these latitudes provide the unique opportunity to reconstruct year-to-year variations in the dominant circulation of middle latitudes in the Southern Hemisphere and evaluate their connections with tropical- and high-latitude climatic forcings such as El Niño and the Antarctic Oscillation.

2. Geographical and historical background

Contrasting climates and complex topography are the main determiners of the current extent of South America tree-ring networks. Trees with distinctive, annual rings are found mainly in temperate forests on the eastern and western slopes of the Southern Andes, from 16°S in the Altiplano to the southern tip of South America at 56°S, spanning more than 2600 km. Tree-ring chronologies and reconstructions have also been developed in the Coastal Range (38°–44°S) and the southern archipelagoes (47°–53°S) in Chile. On the Patagonian steppe, east of the Andes, it is possible to find some shrubs with visible rings but these species have limited values as proxies for climate due to their short life span.

The west central dry lands in Argentina, Chile, Peru and Bolivia, located within the "Arid Diagonal" host several tree species exhibiting annual rings that are visible, although with difficulty, and useful for dendrochronological studies. In subtropical regions with seasonal rainfall, such as northwestern Argentina, several species present clearly visible annual-like rings.

The tropical forest of South America covers ca. 7.885.000 km^2 representing 44.3% of the total land surface of the continent. Many tropical trees do not have distinct ring structures, or the periodicity of the ring-like boundaries is not annual. However, recent advances in tropical dendrochronology have shown several species with conspicuous annual rings that permit the development of chronologies.

During the austral summer of 1949–1950, Edmund Schulman from the Laboratory of Tree-Ring Research, University of Arizona, conducted the first dendrochronological prospective field trip to South America. During his pioneer expedition, Schulman visited Argentina and Chile and developed a preliminary tree-ring chronology with four trees of the moisture-sensitive conifer *Austrocedrus chilensis* in Cerro León (41°05′S, 71°12′W), northwestern Patagonia. Using the same criteria of tree selection applied in the semiarid western United States, he noted that "at this site, 17 km east of Bariloche […] trees apparently reach higher ages than on any other of the visited sites."

Twenty-five years later, LaMarche et al. conducted the first extensive dendrochronological field work in southern South America (1979a,b; Holmes, 1982). LaMarche et al. developed the first set of well-replicated tree-ring chronologies using the conifers *Araucaria araucana* and *Austrocedrus chilensis*.

The pioneer work of LaMarche and Holmes, also included the establishment of the first tree ring laboratory in South America and the training of local scientists from Argentina and Chile in dendrochronological techniques.

During the 80s and 90s, the number of dendrochronologists increased in both countries. As a consequence, research on dendrochronological topics, and the number of publications and chronologies, grew exponentially. Fig. 1 shows the approximate distribution and number of tree-ring chronologies in South America. During the mid 1990s, IGBP–PAGES structured its paleoclimate initiative around three Pole–Equator–Pole (PEP) transects. The Western Cordilleras in the Americas flank the Pacific and encompasses a wide range of environments over 100° of latitude. The PEP-1 transect encompasses mountains that cross most global climate belts, providing the ideal combination of conditions for the development of high-resolution proxy records of climate variability. PAGES facilitated the organization of scientific meetings in the Americas. The Inter-American Institute for Global Change Research (IAI) also provided opportunities to develop integrated, interdisciplinary, and international projects to address climate variability along the latitudinal gradients of the Cordilleras transect. The IAI mandate also stressed the need for studies in the tropical Americas, and the perception that new developments in tropical dendrochronology could provide critical data for understanding the history and dynamics of these environments.

3. Methodological approach

The dating of annual rings and the analysis of the ring characteristics (width, density, and isotopic composition) are common practices for the development of dendrochronological records. Although samples are generally taken using increment borers, the study of cross-sections is presently a common practice in the South American subtropical forests dominated by broadleaf trees with high-density woods. Sample surfaces are carefully sanded to a high polish.

As climate is the major environmental factor influencing tree growth throughout a region, the pattern of interannual variations in ring characteristics from undisturbed individuals, is often similar among trees. As a consequence, the patterns can be matched between trees using a process called cross-dating. This process allows the precise dating of each individual ring to a calendar year. After all rings in each sample are accurately dated, the ring characteristics are properly quantified. For example, the widths of each annual band are measured under a microscope on a sliding stage micrometer, and its value recorded in a data file. Other techniques are used to measure different properties in the wood such as ring density, vessel size or isotopic composition.

The ring-width measurements from each core are standardized by fitting a smooth curve or straight line to the ring-width series. Standardization is the process of removing variability in tree rings that is not related to climate such as tree ageing or forest disturbances. A series of ring-width indices with stationary mean results from dividing each of the observed ring-width value by the associated curve value. Finally, the standardized ring-width measurements from each core are combined into a site chronology, a time series reflecting the common variations in tree growth at the sampling site over time.

Interannual variations in ring width or density are calibrated against climate records over a period of time common to both the climate and the tree-ring record. Once the most appropriate relationship between climate and tree growth is established, a transfer function, describing that climate–ring width relationship, is derived (Woodhouse and Bauer, 2009).

The development of tree-ring chronologies in South America has followed the methodological approach accepted by the international tree-ring community. More detailed descriptions of the methodology can be found in Stokes and Smiley (1968), Fritts (1976), Cook and Kairiukstis (1990) and Schweingruber (1993).

4. Dendrochronology and climatic reconstructions

4.1. Tierra del Fuego and Southern Patagonia (47°S–55°S)

Overview: with the exception of Antarctica and the sub-Antarctic islands, this region represents the southernmost land in the Southern Hemisphere. Its climate is characterized by the continuing pass of

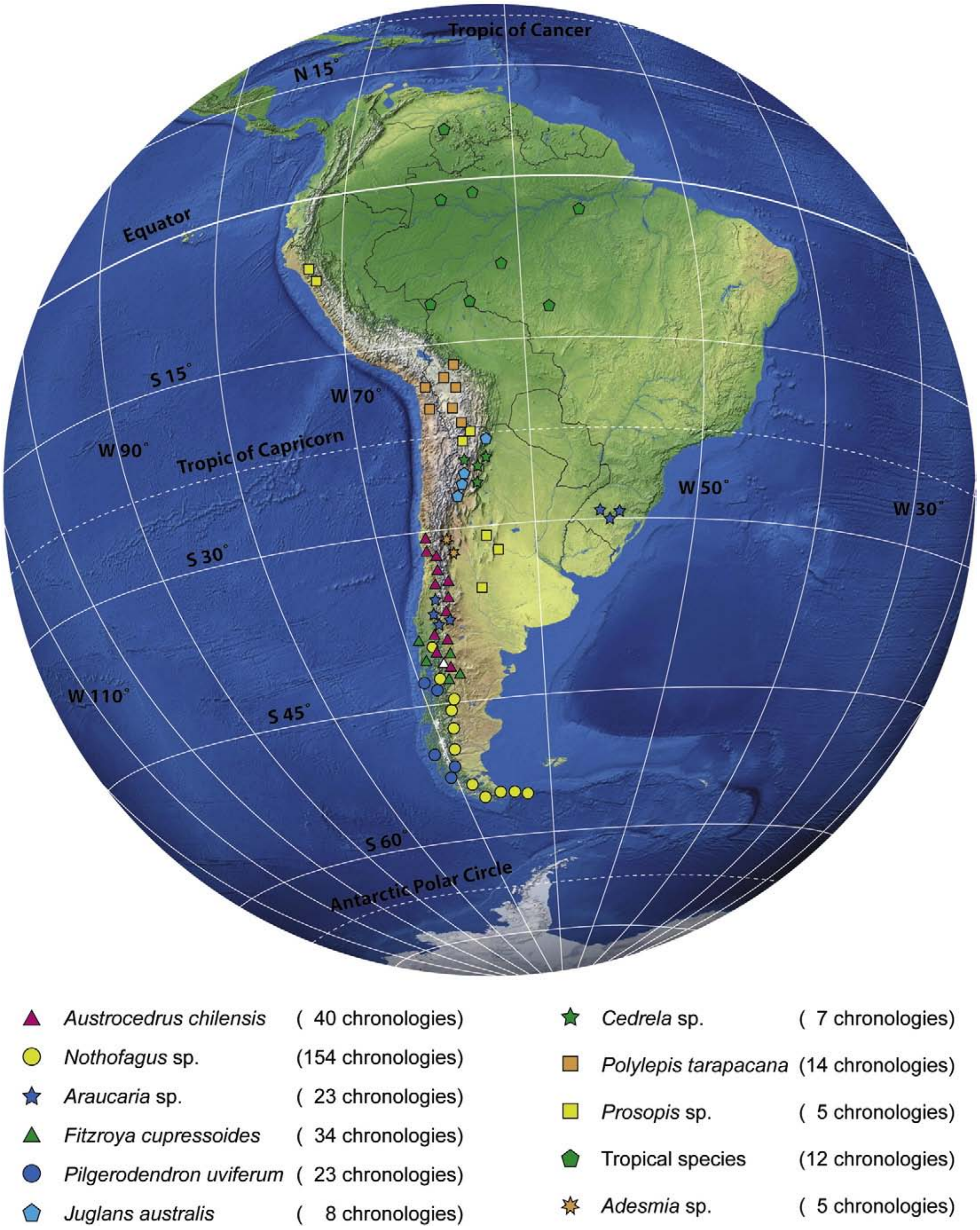


Fig. 1. Tree-ring chronologies in South America. Each symbol represents the approximate location of chronologies. The number of chronologies compiled by the authors and developed from different species is also indicated.

polar fronts, the existence of strong gradients of precipitation between the west and east slopes of the Andes, and particularly steady, strong winds over the eastern Patagonian plateau (Boninsegna et al., 1989).

The main tree species include the South American beeches *Nothofagus pumilio*, *Nothofagus antartica* and *Nothofagus betuloides* along the Andes, and the conifer *Pilgerodendron uviferum* mostly limited to the wetter Chilean part of the region.

Most of the living trees are not older than 400 years, but the combined conditions of cold weather and acidic soils has favored the preservation of stumps, making it possible to extend the dendrochonological time series using subfossil material.

Dendrochronologies developed in this region mainly respond to temperature. However, some *Pilgerodendron uviferum* chronologies developed in the Chilean sector appear to be sensitive to precipitation. Further, chronologies from Tierra del Fuego have been combined with others from New Zealand and Tasmania in studies of the past variability of the sea-level pressure over the Southern Ocean (Villalba et al., 1997b).

4.1.1. Temperature

The first field trip to the Argentinean sector of Tierra del Fuego (55°S) on the southernmost tip of South America in 1986 yielded 21 chronologies from *Nothofagus pumilio* and *Nothofagus betuloides* (Boninsegna et al., 1989). Four of these chronologies were used to reconstruct Ushuaia temperatures from 1750 to 1984, representing a preliminary effort in the use of tree rings to develop proxies for temperature variations in southern South America (Fig. 2c).

In the southern sector of Chilean Patagonia and Tierra del Fuego (51–55°S), 21 tree-ring-width chronologies of *Nothofagus pumilio* were developed by Aravena et al. (2002). Ten of these tree-ring chronologies showed an increasing trend in tree growth from ca. 1960 to 1996, which is concurrent with the increase in temperature shown by instrumental records from southern Patagonia. Based on the positive correlation between tree growth and temperature, Aravena et al. (2002) developed a reconstruction of the minimum annual temperatures at Punta Arenas covering the period 1829–1996. The reconstruction showed that during most of the 19th century, minimum annual temperatures remained below-average and increased to values fluctuating around the long-term mean during the period 1900–1960, followed by an anomalous warming with above-average values after 1963 (Fig. 2b).

More recently, Villalba et al. (2003) reconstructed the dominant pattern of temperature variations in southern South America based on the combined temperature records from Punta Arenas (53°10′S; 70°54′W), Río Gallegos (51°37′S; 69°16′W) and Ushuaia (54°49′S; 68°13′W). Three dendrochronological records were used to reconstruct the dominant pattern of temperature variations in the southern Patagonian sector: a composite chronology from two nearby *Nothofagus pumilio* sites at 1060–1100 m elevation around Lago Cochrane (47°10′S; 72°13′W), Chile; a composite chronology from three individual records located within the Río Narváez catchment (48°S; 72°W), ranging between 930 and 990 m elevation, and a chronology at Piedras Blancas Glacier (49°21′S; 73°00′W) at 650 m elevation. This temperature reconstruction explained 45% of the temperature variance over the interval 1930–1989, and showed an extended cold period from 1640 to 1850, followed by a strong increase in temperature peaking in the 1980s. Important cold events were recorded in 1650–1660s, 1690–1700s, the 1740s, the 1810s and the 1850s. Mean annual temperatures during the 20th century were 0.89 °C above the 1640–1899 mean. The three temperature reconstructions (Fig. 2a,b and c) mentioned above showed a noticeable agreement in interdecadal frequencies. They also showed a coincident and marked trend toward an increase in temperature since 1850.

These findings give a longer historical perspective to the current warming and add new support for the existence of unprecedented 20th century warming in southern South America (Fig. 2a).

4.1.2. Precipitation

Masiokas and Villalba (2004) reported the occurrence of intra-annual bands (or false rings) in a *Nothofagus pumilio* stand growing near the Ameghino Glacier (50°25′ S, 73°10′W), southern Patagonian Andes, Argentina. The stand was used to develop a well-replicated ring-width chronology and a record of intra-annual bands from AD 1760 to 1997. Annual variations in radial growth of *N. pumilio* at this

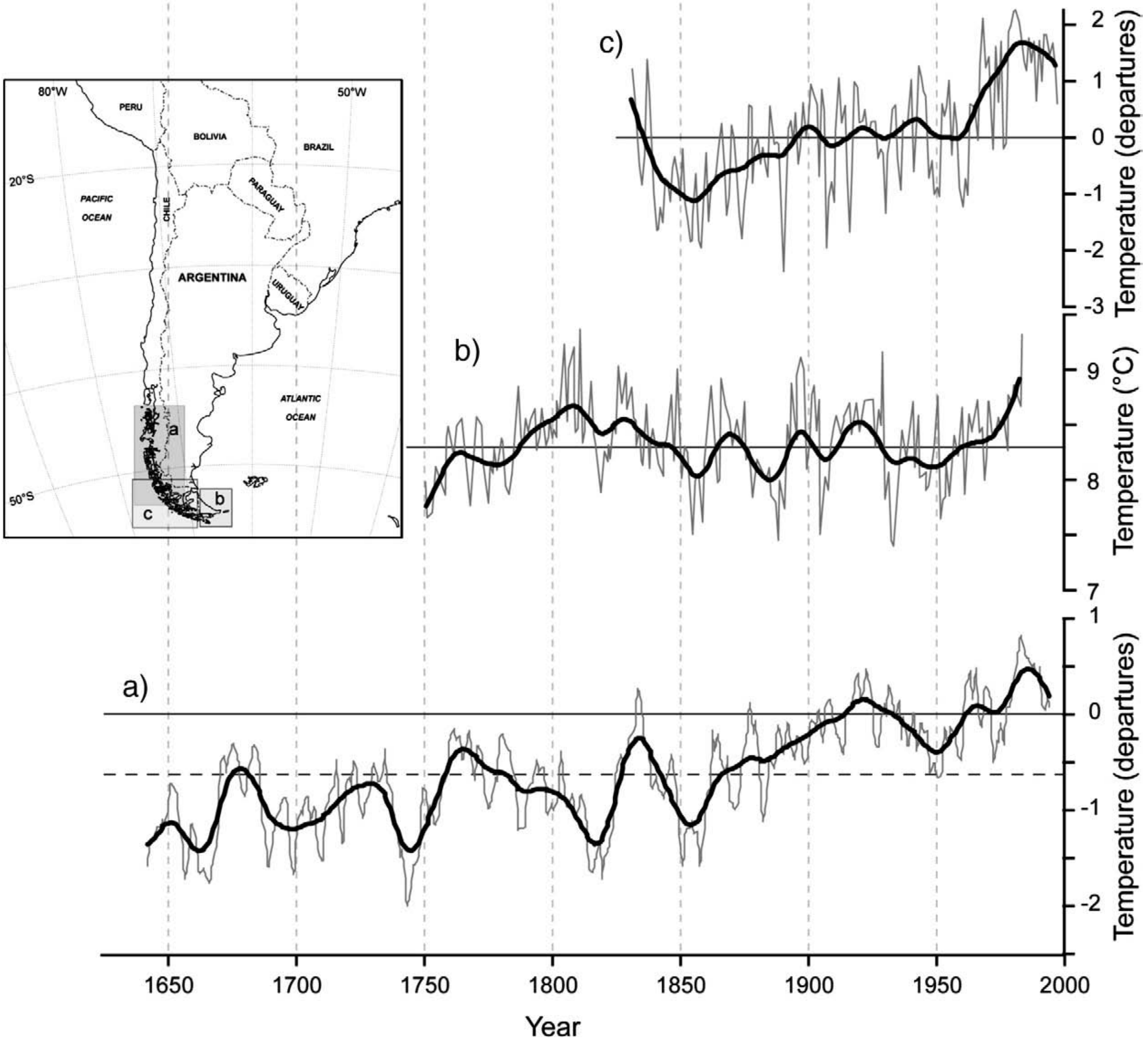


Fig. 2. Temperature reconstructions from the southern part of South America (48°S–55°S) (a) Southern Patagonia (Villalba et al., 2003). (b) Usuahia and Tierra del Fuego Island (Boninsegna et al., 1989.) (c) Chilean southern fiords (Aravena et al., 2002).

site were negatively correlated with spring–summer temperatures and positively correlated with spring precipitation. The formation of intra-annual bands appears to be a response to anomalously dry-warm springs followed by wet-warm late summers. Intra-annual bands may occur in up to 95% of the sampled trees in a given year, and the percentage of trees affected was used as an indication of the strength of the forcing event (Masiokas and Villalba, 2004).

Narrow rings occurred in years following intra-annual band formation, reflecting the lagged effect of unfavorable climatic conditions on tree growth during the subsequent growing season. Intra-annual bands occurred more frequently in the 20th century than the late 18th and 19th centuries. This contrasting pattern seems to be a response to the combination of a long-term warming trend and a significant decrease in precipitation recorded during the last 100 years in this region of southern South America.

Aravena and Luckman (submitted for publication), reported on results from a recently constructed network of 18 tree-ring chronologies from *Pilgerodendron uviferum* in the west coast of southernmost South America between 44° and 55°S. A rotated principal component analysis of the network of *Pilgerodendron* chronologies distinguished the southernmost chronologies as the most significant tree-growth pattern and a second dominant pattern associated with chronologies located close to the southern Patagonia Icefield between 48° and 50°S. The best-correlated combinations of monthly precipitation records and tree-growth series were used to reconstruct two regional rainfall averages. The spring (October–December) precipitation reconstruction for nine northwestern Patagonia stations extends from 1600 to 2002, but explains only 14% of the variance in the instrumental record. The reconstruction of a January-to-June precipitation average from five southern Patagonia stations extends from 1600 to 2000 and explains 40% of the total variance. Both reconstructed series showed oscillation modes for periodicities between 2 and 4 years and between 20 and 40 years but differed in the significance of these periodicities.

4.1.3. Sea-level pressure

The tree-ring chronology network developed from the sub-Antarctic forests provides an opportunity to study long-term climatic variability at higher latitudes in the Southern Hemisphere. Fifty long (1911–1985), homogeneous records of monthly mean sea-level pressure (MSLP) from the southern latitudes (15–65°S) in New Zealand and South America were used to establish a consistent, long-term trans-polar teleconnection pattern during this century. Differences in normalized MSLP between the New Zealand and the South America–Antarctic Peninsula sectors were used to develop a Summer Trans-Polar Index (STPI), which represents an index of sea-level pressure wave number one in the Southern Hemisphere higher latitudes. Tree-ring based reconstructions of STPI showed significant differences in large-scale atmospheric circulation between the nineteenth and the twentieth centuries. Predominantly-negative STPI values during the nineteenth century are consistent with more cyclonic activity and lower summer temperatures in the New Zealand sector during the 1800s. In contrast, cyclonic activity appears to have been stronger in the mid-twentieth century than previously for the South American sector of the Southern Ocean. Recent variations in MSLP in both regions are seen as part of the long-term dynamics of the atmosphere circulation around Antarctica (Villalba et al., 1997b).

4.1.4. Subfossil wood

Roig et al. (1996) reported the discovery of subfossil *Nothofagus* wood buried in several peat bogs in the Argentinean sector of Tierra del Fuego. A provisional, fragmented floating tree-ring-width chronology covering 1400 years was developed. Statistical and spectral analyses revealed no significant differences between the contemporary tree-ring series and this “floating” Tierra del Fuego tree-ring chronology. Some cyclical growth peculiarities were found in both modern and subfossil material. Spectral analysis showed some stability through the last 1400 years especially in oscillatory modes located in the higher frequencies. Peaks centered at a period of ca. 7 years are common for the subfossil series and the present chronologies (Roig et al., 1996; Aravena et al., 2002).

4.1.5. Stable isotopes

Srur et al. (2008) reported on the use of stable isotopes to estimate changes in intrinsic water-use efficiency (IWUE) across an elevation gradient in a *Nothofagus pumilio* forest, located in El Chaltén (49°22′S; 72°55′W), Santa Cruz, Argentina. The relationship between IWUE and climate is more obvious in sites with reduced water stress. In xeric sites, the photosynthetic rate is severely limited by water deficits so that the reduction in radial growth is not compensated by the increase in IWUE. In contrast to the traditional assumption in dendrochronology that the strong relationships between radial growth and climate are recorded at the forest ecotones, the variations in δ^{13}C better reflected water deficits at intermediate mesic sites.

4.2. Northern Patagonia (37°S–46°S)

Overview: mean annual temperatures across Patagonia are mainly influenced by latitude, elevation and proximity to the ocean. A typical west–east profile of precipitation at 40°S would show ca. 1500 mm/year at the Chilean coast and about 3500 mm/year at the main Andean divide, abruptly decreasing to ca. 300 mm/year in the xeric Patagonian steppe, ca. 50 km to the east of the mountains. Vegetation is characterized by high species diversity with several endemic species to the region. This is especially true in the Valdivian rainforest ecoregion, at the Chilean slope of the Andes. Arboreal taxa are also numerous, several of them with very suitable characteristics for dendrochronology: longevity, easy visualization of the rings, circular uniformity and good cross-dating. The longest chronologies of South America were obtained from this region, developed with living *Fitzroya cupressoides* and extending more that 2500 years. Other species also exhibit remarkable longevity, such as *Austrocedrus chilensis* (>1000 years old) and *Araucaria araucana* (>900 years old). *Nothofagus* are also quite well represented in this region and occupy a major portion of the forest strata, reaching a more or less continuous tree line. The climate-growth relationship is strongly dependent of the site. At the border with the Patagonia steppe, most of the trees are sensitive to precipitation, while near the upper tree line temperature appears to be the most important growth-limiting factor (Villalba and Veblen, 1997). In fact, careful selection of sample sites has permitted the reconstruction of both precipitation and temperature in the region.

4.2.1. Temperature

Villalba et al. (1989) made the first attempt to provide a quantitative estimate of temperature variations in northern Patagonia. Sixty years (1914–1973) of a regional temperature record were regressed against seven *Araucaria auracana* chronologies developed by LaMarche et al. (1979a,b) to provide a summer temperature reconstruction that covers the interval 1500–1973. The reconstruction accounts for 49% of the total variance in the observed temperature record.

During the 1980s, millennial chronologies were developed from *Fitzroya cupressoides* (Mol.) Johnst (alerce) in Argentina (Boninsegna and Holmes, 1985; Villalba, 1990a,b) and in the 1990s in Chile (Lara and Villalba, 1993). Lara et al. (2000) reported the construction of a network of 23 *Fitzroya* chronologies (14 from Chile and 9 from Argentina), 19 of them over 1000 years in length. Regional-scale growth patterns and correlation among the chronologies showed a strong common signal. Principal component analysis of the 17 longest chronologies showed that the first eigenvector explains 42.2% of the total variance and the weighting of the chronologies in the component do not differ significantly. This result indicated the existence of a regional environmental factor modulating *Fitzroya* growth, which was attributed by the authors to climate parameters (temperature, precipitation or interactions of both).

Villalba (1990a,b) used a millennium-old *Fitzroya cupressoides* chronology to develop a 1120-year reconstruction of summer temperature departures for the Andes of northern Patagonia in Argentina (Fig. 3b). The chronology used in the reconstruction was built up using methods that do not preserve much of the low frequencies. However, four main climatic episodes were identified in this paleoclimatic record. The first, a cold and moist interval from AD 900 to 1070, was followed by a warm-dry period from AD 1080 to 1250, concurrent with the Medieval Warm Epoch in Europe. Afterward, a long, cold-moist period followed from AD 1270 to 1670, peaking around AD 1340 and 1650. These cold maxima are contemporaneous with Little Ice Age glacial events registered in the Northern Hemisphere. Warmer conditions then resumed between AD 1720 and 1790. These episodes are supported by glaciological data in Patagonia. Following a cold period in the early 1800s, tree-ring indices oscillated around the long-term mean, except for a warmer period from AD 1850 to 1890. No warming trend was detected for the period AD 1890–1986.

A tree-ring-width chronology of *Fitzroya cupressoides* from Lenca (41°37′S–72°40′W), southern Chile, was used to produce an annually resolved reconstruction of mean summer (December to March) temperature for west Northern Patagonia (Lara and Villalba, 1993). This temperature reconstruction extends for 3620 years and is the longest temperature tree-ring based reconstruction in South America (Fig. 3a). The longest interval with above-average temperatures was from 80 BC to AD 160. Long intervals with below-average temperatures were recorded from AD 300 to 470 and from AD 1490 to 1700. Both *Fitzroya*-based reconstructions derived from single chronologies are well correlated during their common interval 869–1984. However, the reconstructions maximize the high-frequency variance present in the relatively short meteorological record available for Northern Patagonia, losing much of the long-term information contained in the tree-ring series.

Villalba et al. (1996) reported a new regional tree-ring record derived from eight temperature-sensitive *Fitzroya* chronologies for the past 1000 years (Fig. 3c). The chronologies were conservatively standardized to preserve a large part of the low frequency variation. Spectral studies revealed the presence of characteristic long-term oscillatory modes, particularly with periods of 77, 50, 34, 24, 21 and 11 years. External solar forcing, such as the 11-year sunspot cycle, the 22-year Hale cycle and the 80-year Gleisberg cycle, were invoked to explain the existence of some of the reported oscillations.

Traditionally, trees growing at upper tree line are considered to be more sensitive to temperature variability and therefore Lara et al. developed a network of tree line sites for *Nothofagus pumilio*. This species is the dominant subalpine species from ca. 35°35′ to 55°S along the southern Andes of Chile and Argentina (Lara et al., 2005a; Villalba et al., 1997a). This network of more than 90 *N. pumilio* chronologies was developed from both sides of the Andes. The availability of this relatively large, uniformly distributed set of upper elevation chronologies across the northern and southern Patagonian Andes allowed the development of local and regional reconstructions of temperature.

Villalba et al. (1997a) developed 15 tree-ring chronologies from *Nothofagus pumilio* growing from between 1200 to 1750 m in elevation on the Argentinean side of the northern Patagonian Andes. Trends in tree-ring characteristics and variations in the relationships between tree growth and climatic fluctuations were examined along this altitudinal gradient. Annual variation in the growth of the subalpine *N. pumilio* was related to variations in mean annual temperature and duration of snow cover. Based on these relationships, multiple regression models were developed to reconstruct the duration of snow cover and mean annual temperature fluctuations in the subalpine zone of northern Patagonia since AD 1750. Abrupt interannual changes in the mean annual temperature reconstruction are associated with strong to very strong El Niño Southern Oscillation events. At the upper tree line, tree growth has been anomalously high since 1977. Temperatures in northern Patagonia have been anomalously high throughout the 1980s, which is consistent with positive temperature anomalies in the tropical Pacific and along the western coast of the Americas at ca. 40°S latitude. The 250-year temperature reconstruction indicates that although the persistently high temperatures of the 1980s are uncommon during this period, they are not unprecedented. Tropical climatic episodes similar to that observed during the 1980s may have occurred in the region in the recent past under pre-industrial carbon dioxide levels.

Nothofagus pumilio tree-ring records from the upper tree line were used to reconstruct past temperature fluctuations in northern Patagonia (Fig. 3d). The resulting reconstructions explain 55% of the temperature variance over the interval 1930–1989. This reconstruction is especially useful for studying multi-decadal temperature variations in Patagonia over the past 360 years. It shows that the temperatures during the 20th century have been anomalously warm across the southern Andes. The mean annual temperature for the northern sector during the interval 1900–1990 is 0.53 °C above the 1640–1899 mean. Significant cold events are centered on 1650–1660, 1700 and from 1820 to 1870. The rate of temperature increase from 1850 to 1920 was the highest over the past 360 years, a common feature observed in several proxy records from higher latitudes in the Northern Hemisphere (Overpeck et al., 1997). These findings are concordant with the temperature reconstructions of the southern Patagonia (Villalba et al., 2003) and place the twentieth century warming in a longer historical perspective, adding new support for the existence of unprecedented warming over Patagonia.

4.2.2. Precipitation

Precipitation variations in northern Patagonia have been reconstructed for both sides of the Andes. The first attempt to estimate past precipitation variations in the eastern slopes of the Andes was conducted by Schulman (1956) near San Carlos de Bariloche, Argentina. Based on four *Austrocedrus chilensis* (D.Don) Endl trees growing on Cerro Los Leones (41°S; 71°W), he developed a 378-year chronology covering the interval 1572–1949, which provided a first indication of precipitation variations in the region.

More recently, seasonal and annual precipitation reconstructions were developed for northern Patagonia east of the Andes, using a set of 16 tree-ring-width chronologies from *Austrocedrus chilensis* (Villalba et al., 1998a,b). Reconstructions, which capture between 41 and 50% of the precipitation variance, show that the 20th century contains the most extreme, long periods of wetness and dryness. For the past 400 years, the precipitation reconstructions show that the driest and wettest 25-year periods are 1895–1919 and 1925–1949, respectively. Average departures for these two 25-year intervals are at least two standard errors from the long-term means (Fig. 4c).

A precipitation reconstruction for south-central Chile (35°40–38°40 S) was developed from *Nothofagus pumilio* trees growing at high elevation near the tree line (1500–1700 m elevation, Lara et al., 2001). The *N. pumilio* radial growth on dry sites near its northern distribution limit is positively correlated with late spring and early summer precipitation. In contrast, above-average temperatures reduce radial growth, due to an increase in evapotranspiration rates and decrease in soil water availability. A reconstruction of November–December (summer) precipitation for the period 1837–1996 from *N. pumilio* tree-ring chronologies accounted for 37% of instrumentally recorded precipitation variance. The periods 1890–1914 and 1917–1941 appear as the driest and wettest 25-year periods within the reconstruction, respectively. These driest and wettest periods coincide very closely with those described by Villalba et al. (1998a,b) in a precipitation reconstruction from *Austrocedrus chilensis* growing in the dry forest–steppe ecotone of Northern Argentinean Patagonia (Fig. 4a).

This study also indicates that the dominant patterns of sensitivity of *Nothofagus pumilio* to climate at tree line vary with latitude, from precipitation- to temperature-sensitive with increasing latitudes

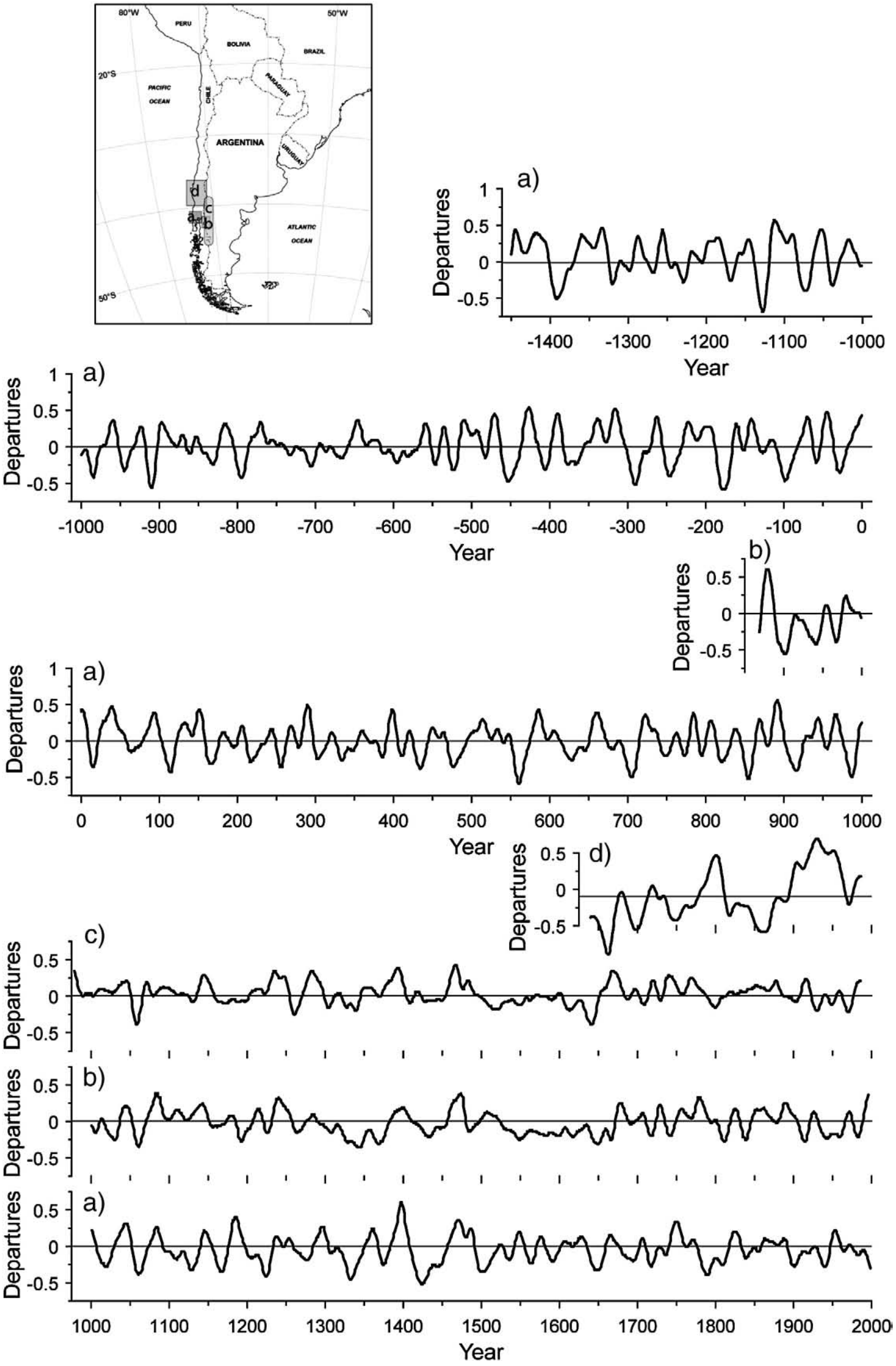


Fig. 3. Northern Patagonia temperature reconstructions filtered with a 25-pass cubic spline to emphasize the low frequencies. (a) *Fitzroya cuppressoides* at Lenca (Lara and Villalba, 1993); (b) Rio Alerce *Fitzroya cuprresoides* (Villalba, 1990a,b); (c) *Fitzroya cupressoides* regional (Villalba et al., 1996); (d) upper tree line *Nothofagus pumilio* (Villalba et al., 1997a).

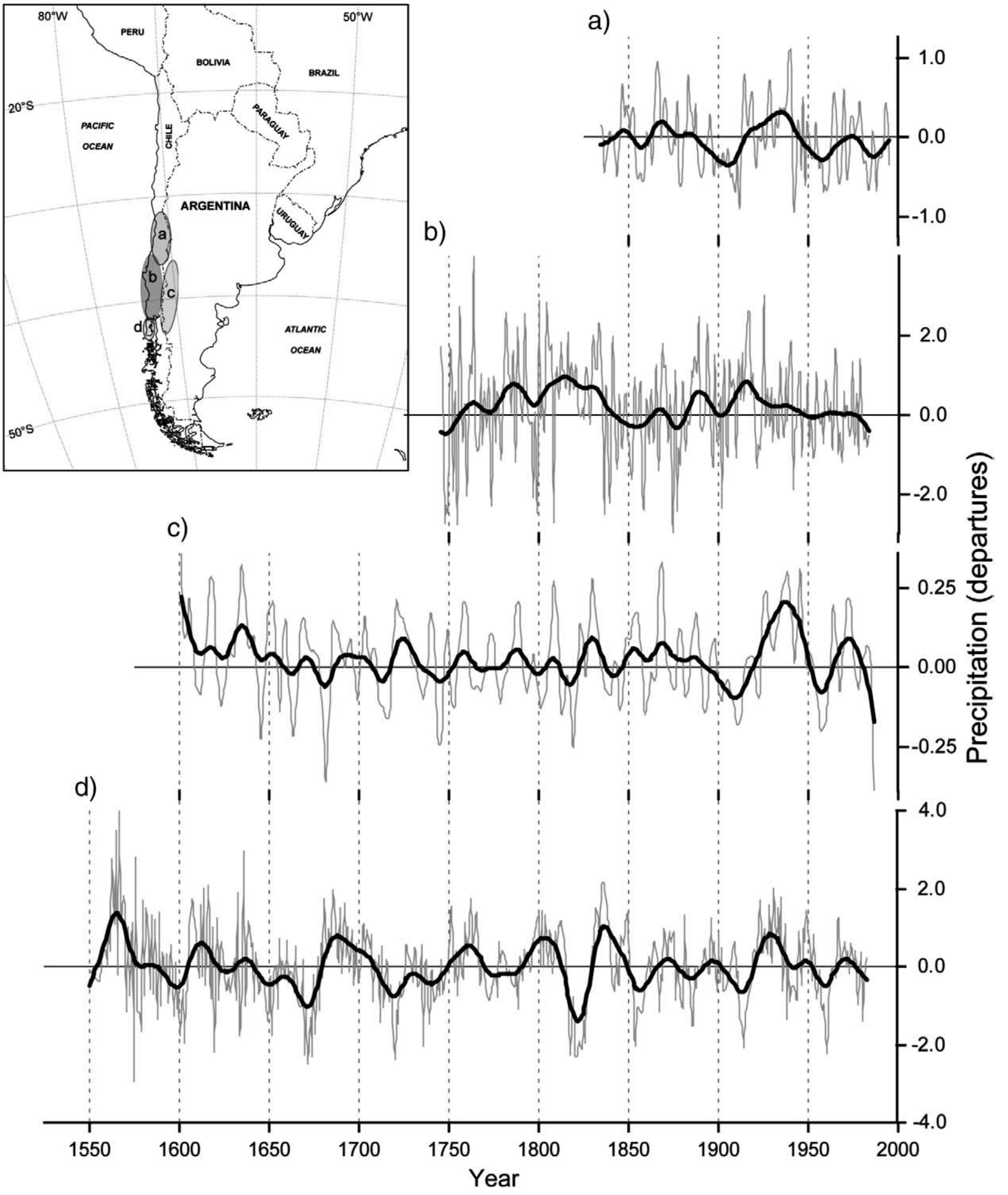


Fig. 4. Northern Patagonian precipitation reconstructions. (a) *Nothofagus pumilio* from tree line (Lara et al., 2001). (b) Snow-cover reconstruction (Villalba et al., 1997a). (c) *Austrocedrus chilensis* annual precipitation reconstructions (Villalba et al., 1998a,b). (d) Chiloe island *Pilgirodendron uviferum* reconstructions (Roig and Boninsegna, 1992).

(Lara et al., 2005a). The recent increase of precipitation variability in northern Patagonia may reflect stronger interactions between middle and high-latitude atmospheric circulation in the Southern Hemisphere during the 20th century (Montecinos and Aceituno, 2003).

On the Pacific insular area of northern Patagonia (43°S), past variations in summer precipitation back to 1557 were inferred from two chronologies of *Pilgerodendron uviferum* for the Chiloe Island (Roig and Boninsegna, 1992). The reconstruction, which explains 32% of the summer precipitation variability, points out the existence of marked reduction in rainfall during five drought intervals, in particular during the years 1815–1829 (Fig. 4d).

4.2.3. Snow cover

Above-average precipitation during late spring, which in turn prolongs the snow cover and delays the soil warming, reduced the growth of *Nothofagus pumilio* at the tree line in northern Patagonia. Due to lack of a snow-cover record from northern Patagonia, Villalba et al. (1997a) built up a snow-cover index using a combination of monthly precipitation for November, December and January, and temperature for November and December from seven stations in the area. The Snow Cover Index (SCI) agrees with the sparse available records of snow accumulation and indirect observations of snow depth in the region. A subset of 41 long-lived trees sensitive to snow-cover variations were selected by comparing correlations of individual tree, standardized ring-width series against the SCI for the interval 1918–1984. A combination of principal component and best subset regression analysis were used to reconstruct SCI for the interval 1750–1984. The duration of the snow cover was above the long-term mean from 1780 to 1830, decreased from 1840 to 1880 and peaked again during the 1890s and late 1910s–early 1920s. The SCI reconstruction shows a trend towards increased length of the snow-free period during the past 50 years (Fig. 4b).

4.2.4. River flow reconstructions

Holmes et al. (1979) conducted the reconstruction of the Rio Neuquén and Rio Limay streamflows using seven chronologies of *Araucaria araucana* and *Austrocedrus chilensis* from northern Patagonia. The annual runoff of both rivers was reconstructed back to the year 1601 using canonical analysis. The predicted variables were the gauged annual river flow data from the Neuquén and Limay rivers and the predictors each of the seven sites. The correlation coefficient between the measured and estimated records was $r = 0.73$ in both cases. The reconstructed runoff series showed important low flow periods between 1630 to 1750 and 1890 to 1925, while high flows during the period 1760 to 1830 (Fig. 5a and b).

The Puelo River is a bi-national watershed between Chile and Argentina with a mean annual streamflow of 644 $m^3 s^{-1}$. Lara et al. (2005b, 2008) used *Austrocedrus chilensis* and *Pilgerodendron uviferum* tree-ring records to reconstruct the summer–fall (December to May) Puelo River streamflow. *A. chilensis* grows in the dry environments of the forest–steppe ecotone, whereas *P. uviferum* occurs in humid rainforests and bogs. Interestingly, despite the contrasting environments in which these species grow, in all the sites studied they showed a similar response function with a positive significant correlation with prior summer–fall streamflow. The reconstruction goes back to 1599 and has an adjusted r^2 of 0.42. Spectral analysis of the reconstructed streamflow showed a dominant 84-year cycle, which explained 25.1% of the total temporal variability. The Puelo River summer–fall streamflow showed a significant correlation ($P > 0.95$, 1943–2002) with hydrological records within the Valdivian ecoregion in Chile and Argentina (35° to 46°S). Summer–fall streamflows showed a significant negative correlation with the Antarctic Oscillation (AAO), whereas winter–spring anomalies appeared to be positively connected with sea surface temperature variations in the tropical Pacific. In general, above- and below-average discharges in winter–spring are related to El Niño and La Niña events, respectively. The temporal patterns of the observed and reconstructed records of the Puelo River streamflow showed a general decreasing trend in the 1943–1999 periods (Fig. 5c).

4.2.5. Fire history

Kitzberger et al. (1997) examined the influences of annual climatic variations on fire occurrence along a west–east rainfall gradient from temperate rainforests to xeric woodlands in northern Patagonia. Fire chronologies were derived from fire scars on trees and related to tree-ring proxy records of climate over the period 1520–1974. Fire in *Nothofagus* rainforests seems highly dependent on drought during the

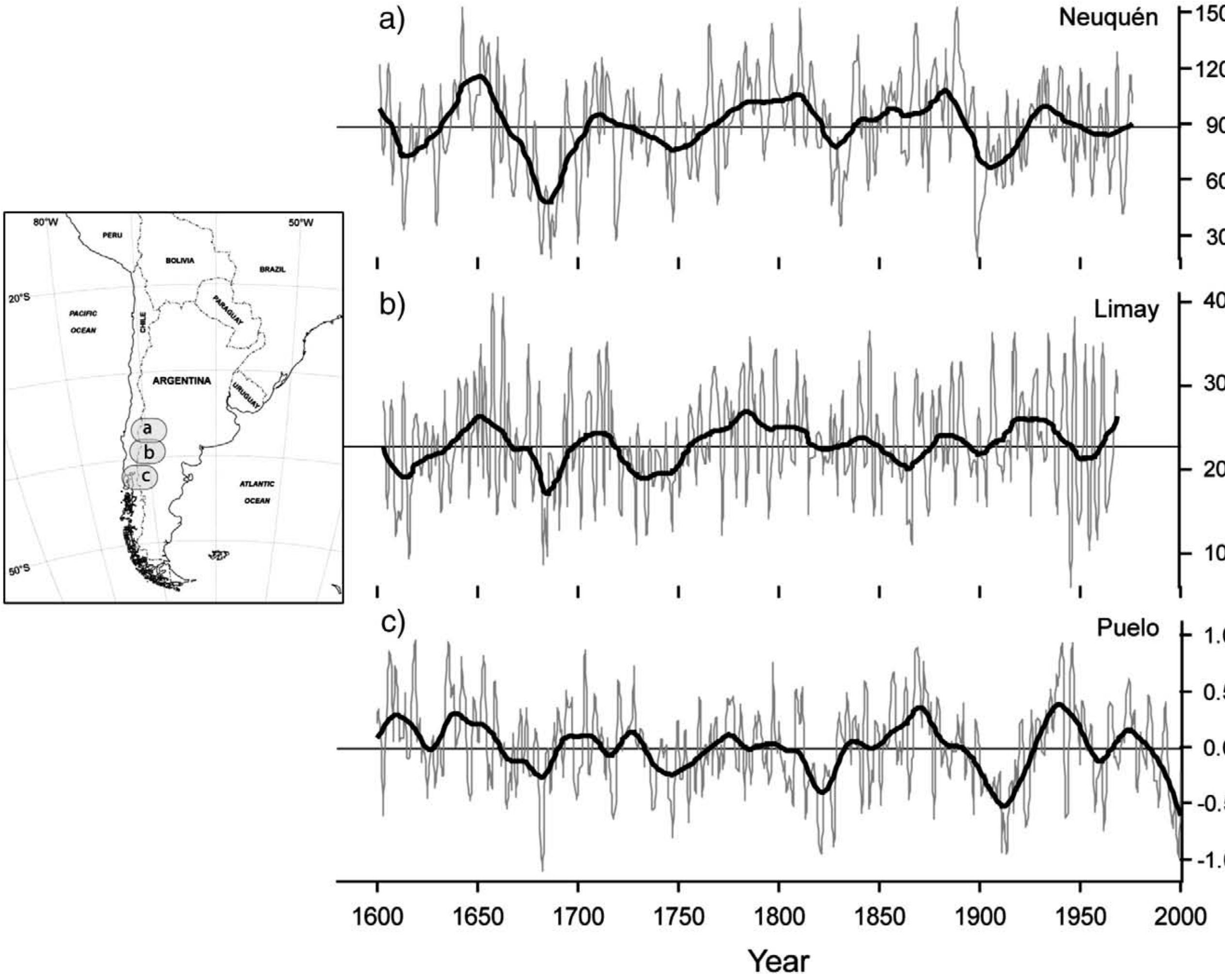


Fig. 5. Streamflow reconstructions. (a) Neuquen and (b) Limay (Holmes et al., 1979). (c) Rio Puelo (Lara et al., 2008).

spring and summer of the year in which fires occur. In xeric *Austrocedrus* woodlands, fire occurrence and spread are promoted by droughts during the fire season and by above-average moisture conditions during the preceding 1 to 2 growing seasons, which enhances fuel production.

Lara et al. (1999) studied the widespread mortality of *Fitzroya cupressoides* (alerce) throughout the Coastal Range of south-central Chile. They showed that fire was the main cause of tree mortality was, and fires were dated to have occurred between 1397 and 1943, indicating that they have occurred repeatedly at least over the past 600 years. Since the time of European settlement in southern Chile (ca. 1750), fires have mainly been caused by human activities; however, prior to that time, fires were probably caused by both lightning and native people that inhabited the area.

The effects of humans and climatic variation on fire history in northern Patagonia, Argentina, were examined by dating fire scars on 458 trees at 21 sites in rain forests of *Fitzroya cupressoides* and xeric woodlands of *Austrocedrus chilensis* from 39° to 43°S latitude (Veblen et al., 1999). Climatic variations associated with fires were analyzed on the basis of 20th-century observational records and tree-ring proxy records of climatic variation from approximately AD 1500. In the *Austrocedrus* woodlands, fire frequency increased after about 1850, probably due to an increase in human activity in the region. Strong synchronicity in the years of widespread fire over long distances indicates a strong climatic control at the annual scale. Tree-ring reconstructions of regional precipitation and temperature show less influence of climatic variability on fire occurrence at multi-decadal scales.

Gonzalez et al. (2005) examined the fire history of *Araucaria–Nothofagus* forests in the Andes cordillera of Chile. Based on a combination of fire-scar proxy records and forest stand ages, they reconstructed fire frequency, severity and the spatial extent of burned areas for approximately 4000 ha. Over 1696 to 2000, fire-scar dates from *Araucaria* and *Nothofagus* showed that the composite mean fire interval varied from 7 years for all fires to 62 years for widespread events.

4.2.6. Subfossil wood

Roig et al. (2001) reported a floating 1229-year chronology developed from subfossil stumps of *Fitzroya cupressoides* in southern Chile that dates back to approximately 50,000 C-14 years before present. The chronology was used to calculate the spectral characteristics of climate variability at this time, which was probably an interstadial period. Growth oscillations at periods of 150–250, 87–94, 45.5, 24.1, 17.8, 9.3 and 2.7–5.3 years were identified in the annual subfossil record. A comparison with the power spectra of chronologies derived from living *F. cupressoides* trees showed strong similarities with the 50,000-year-old chronology, indicating that similar growth forcing factors operated in this glacial interstadial phase as in the current interglacial conditions.

4.3. Andes (28°S–37°S)

Overview: the Andes from 28°S to 37°S are characterized by a Mediterranean-type climate, with mild-wet winters and dry summers. The blocking effect of the high-pressure cell on the southeast Pacific Ocean inhibits precipitation in summer, while during winter the Westerlies reach this region generating frontal precipitation. Total annual precipitation at high elevations (above 2500 m) ranges from less than 500 mm in the north (31°S) to as much as 2000 mm at 36°S. Forests are in general patchy, with trees growing in open stands. *Austrocedrus chilensis* dominates the region landscape, often in the form of relic stands. In the southern part of the region, some *Nothofagus* forests are present, which constitutes the northern limit of the genera expansion.

There are no tree-ring based temperature reconstructions presently available for the Andes between 28°S and 37°S. In the semiarid Andes, tree growth is strongly controlled by precipitation, even close to tree lines. Thus, the temperature signal in tree rings is poor and not strong enough to allow reconstructions. At these latitudes, temperature affects tree growth indirectly by modulating moisture availability, because higher temperatures increase evapotranspiration. Therefore, moisture indices such as the Palmer Drought Severity Index (PDSI), accounting for temperature and precipitation, are especially well-suited for reconstruction at this latitudinal band.

4.3.1. Precipitation

LaMarche (1975) developed the first network of tree-ring chronologies in the Southern Hemisphere and provided the first estimates of winter precipitation variations from Santiago de Chile during the past seven centuries (LaMarche et al., 1979a,b). This early reconstruction was based on a single chronology from *Austrocedrus chilensis* at El Asiento (32°39′S; 70°56′W), a semiarid relict stand located north of Santiago de Chile. A careful examination of the relationships between precipitation variations in Santiago and tree growth for each individual core in El Asiento, provided Boninsegna (1988) with a new criterion for selecting a subset of samples strongly correlated with climate. Based on this subset, a new reconstruction of winter rainfall at Santiago de Chile back to 1220 was developed.

More recently an updated and robust network of moisture-sensitive tree-ring chronologies has been developed for central Chile. A composite record consisting of El Asiento and El Baule (34°29′S¸70°22′W) chronologies were used by Le Quesne et al. (2006) to develop new estimates of June–December precipitation extending from AD 1200 to 2000. The reconstruction suggested that the decadal variability of precipitation in Central Chile was greater before the 20th century, with more intense and prolonged dry and wet episodes. Multi-year drought episodes in the 18th, 17th, 16th, and 14th centuries exceeded the estimates of decadal drought during the 20th century. The reconstruction also indicated an increase in interannual variability after 1850. In fact, the risk of drought increased dramatically in the reconstructed precipitation series after 1850, consistent with the drying trends indicated by the longest instrumental precipitation records.

Le Quesne et al. (2009-this issue), using a similar set of tree-ring chronologies but with a different detrending procedure, reconstructed the Santiago de Chile annual precipitation and compared the series with Central Andes glaciers retreat.

4.3.2. Anticyclone position

Villalba (1990a,b) used a combination of 22 tree-ring chronologies to establish the dominant patterns in tree growth in the Andean Cordillera from 32°S to 43°S. The chronologies were derived from *Austrocedrus chilensis*, *Ararucaria araucana*, *Fitzroya cupresoides*, and *Nothofagus pumilio*.

Three dominant patterns were recorded. The *Austrocedrus* chronologies from El Asiento, San Gabriel, and Huinganco showed a common pattern of tree growth. The amplitude of the first eigenvector from these chronologies was used to estimate the position of the surface subtropical high-pressure belt along the Chilean coast during the winter. A second pattern, related to the chronologies from Cuyin Manzano (40°46′S; 71°11′), Cerro Los Leones (41°S; 71°07′W) y Estancia Teresa (42°56′S; 71°13′W) in northern Patagonia, was related to the position of the anticyclone cell during the austral summer.

4.3.3. Streamflow

Cobos and Boninsegna (1983) reconstructed the streamflow of the Atuel River (35°S, 69°40′W) using three *Austrocedrus chilensis* chronologies derived from sites on the Chilean slope of the Cordillera, between 32°40′ and 35°00′S. Boninsegna and Delgado (2002) revisited the Atuel runoff reconstruction, emphasizing the influence of solar and ENSO forcing on the streamflow variations. Annual flow was reconstructed back to 1575. The correlation between measured and reconstructed series was $r = 0.71$ (i.e., 50.4% of the total variance explained by the model). The reconstructed streamflow series did not exhibit periods of greatly increased runoff, except from 1820 and 1850. In this series, 50% of the annual flows were above the long-term mean between 1575 and 1850, 33% between 1850 and 1914, but only 25% between 1914 and 1970. Thus, the proportion of years with streamflows below the mean has lately increased.

Snow accumulation in the Andes Cordillera tends to be larger during ENSO years at the same latitude. The streamflow of the Atuel River is dependent on the snow accumulated in the upper basin. The probability distribution of the annual flow clearly showed that during the summer following an ENSO year, the discharge will probably be larger than during non-ENSO events. Spectral techniques applied to the Atuel reconstructed series indicated the presence of oscillatory modes at periods of 78.5, 21.4 and 12.2 years, which account for 21%, 6% and 15% respectively of the total variance, respectively. These results suggested some degree of influence of the solar forcing in the low frequency component of the long-term river discharge.

4.3.4. Stable isotopes

In a first attempt to use isotopes in tree rings in South America, Leavitt and Lara (1994) documented a declining trend of $\delta^{13}C$ in *Fitzroya cupressoides* rings in southern Chile.

Roig et al. (2006) reported the development of the first annually resolved $\delta^{18}O$ tree-ring chronology obtained from *Austrocedrus chilensis* trees growing in the foothills of the northeastern Patagonian Andes. The isotope record spans between 1890 and 1994. The authors explored the probable links between this record and the climate of the region. Air temperatures during summer were significantly correlated with annual $\delta^{18}O$ values from *Austrocedrus* tree rings. The strongest correlations were between the Southern Oscillation Index (SOI) and tree rings. The existence of millennial-age *Austrocedrus* trees in northern Patagonia provides interesting possibilities for examining these climate-related isotopic signals over the last thousand years.

4.3.5. Palmer Drought Severity Index

Christie (2008) utilized a tree-ring network of *Austrocedrus chilensis* to reconstruct the Palmer Drought Severity Index (PDSI) in the Andes region located between 35.5° and 39.5°S. The reconstruction covered the last 657 years capturing the interannual and decadal late spring–early summer PDSI variability and described the latitudinal north–south interannual oscillation in moisture conditions between the Mediterranean and Temperate climates. An increment in the interannual variability since ~1730, with three significant ~30 year long peaks centered on 1750, 1849, and 1940, was observed in the reconstructed record. The reduction of variance after 1950 was associated with an increase (decrease) of extreme negative (positive) PDSI values. Return time analysis showed that the risk of drought increased during 1920–2002 when compared to the previous 1346–1919 reconstructed period. Moisture conditions in the region was linked to Niño-3.4 Sea Surface Temperature (SST) during spring and strongly negatively correlated with the Antarctic Oscillation (AAO) during summer. The twentieth century increment of extreme drought events may not be related to ENSO but to the positive AAO trend during late spring and summer resulting from a gradual poleward shift of the mid-latitude storm tracks.

4.4. The Arid Diagonal

The South American Arid Diagonal (Garleff et al., 1991; Villagrán et al., 1998) is a broad band of land with reduced precipitation (<250 mm/year) that extends obliquely across the continent from the Guayaquil gulf (2°30′S, 80°00′W) in Ecuador to Chubut province (43°45′W) in Argentina. It represents the limits of the Atlantic and Pacific domains in the west part of the continent, and comprises several regions with different landscapes and vegetations according to latitudinal and altitudinal gradients.

4.4.1. Puna and Altiplano

Polylepis tarapacana is a small tree growing in the Bolivian Altiplano and adjacent areas of Peru, Chile and Argentina (16–22°S) between 4000 and 5200 m elevation. Collections of *P. tarapacana* were gathered from the Bolivian Altiplano between 2001 and 2004, at more than 17 sites across the Cordillera Occidental. These collections yielded 14 chronologies from *P. tarapacana* (Argollo et al., 2004; Solíz et al., 2009-this issue). The chronologies range between 98 and 705 years in length, and represent the highest tree rings records worldwide.

Additional *Polylepis tarapacana* chronologies have been developed in northern Chile (17°40′–21°20′S; Moya and Lara, 2003) and in Cerro Granados, northwestern Argentina (22°32′S; 66°32′W, Morales et al., 2004).

In order to determine the climatic variables controlling *Polylepis tarapacana* growth, interannual variations in tree growth were compared with regional records of precipitation and temperature (Argollo et al., 2004). Contrasting responses of *P. tarapacana* to temperature during the previous and current growing season were registered at most sites. Temperatures above the long-term mean during the previous growing season resulted in increased evapotranspiration, reduced water supply, and consequently were negatively correlated to tree growth. During the current growing season, temperatures were positively related to radial growth from January to March, suggesting a positive effect on tree growth. Argollo et al. (2004) and Morales et al. (2004) argued that this response of radial growth to temperature is, to some extent, a function of the particular characteristics of temperature oscillations rather than a consistent response of trees to climate in the Puna.

For precipitation, the most conspicuous pattern was the large number of sites showing significant positive responses from November to March during the previous growing season and relationships with January were statistically significant at most sites. During the current growing season, negative correlations with December rainfall were registered at few sites. This indicates that the radial growth of *Polylepis tarapacana* along the Cordillera Oriental is favored by above-average precipitation during the previous growing season. These records offer the unique opportunity for reconstructing precipitation and temperature variations across the Altiplano during the past 5–7 centuries (Solíz et al., 2009-this issue).

Christie et al. (2009—this issue) used two tree-ring chronologies to analyze the regional climate and ENSO influences on *Polylepis tarapacana* growth at the east and west Andean slopes on the Chilean Altiplano. Tree growth was positively correlated with spring–summer tropical Pacific SSTs, with a spatial pattern resembling to ENSO wedge. In general, El Niño (La Niña) events are well recorded in the chronologies, determining above (below) mean anomalies on tree growth. *P. tarapacana* chronologies offer a good opportunity to future multi-proxy ENSO reconstructions.

Due to the scarcity of species with annual rings, the use of dendrochronological techniques has received little attention in tropical and subtropical montane dry areas. Recently, Morales et al. (2001) assessed the dendrochronological potential of *Prosopis ferox* through the analysis of its wood anatomy and the relationships between climate and tree-growth variations from trees collected at 3500 m in the Humahuaca valley (23°13′ S, 62°20′ W), Jujuy, Argentina. Microscopic observations showed that annual rings are clearly defined by a relatively lighter parenchyma belt formed at the end of the annual band. Comparisons between the standardized ring-width chronology and the instrumental records from La Quiaca (22°06′S, 65°36′W) indicated that above-average rainfall and below-average temperature during summer (i.e., December to March) favor tree growth. This chronology represents the first dendrochronological record from *P. ferox*. The well-defined annual rings, the strong relationship between growth and climatic variables, the large range of distribution across northwestern Argentina and southern Bolivia (20° to 25°S), and the longevity observed in some individuals (c. 500 years), indicate that *P. ferox* is a very promising species for dendroclimatological and dendroecological studies in subtropical montane ecosystems.

4.4.2. Dry-land shrubs

Several studies have identified tree and shrub species with suitable dendrochronological characteristics to fill the gaps in the chronology network in drylands, especially in Argentina, Chile and Peru. Roig (1987) studied the mortality of high altitude *Adesmia horrida* shrubby trees, which occurs due to heavy snow accumulation in the Mendoza Cordillera. Growth in *Adesmia* was found to be more closely related to precipitation than to temperature recorded at the nearby meteorological stations (Roig and Boninsegna, 1990).

The first chronology using *Prosopis flexuosa* was developed by Villalba and Boninsegna (1989) at Chancani (31°23′S; 67°65′W), Cordoba, Argentina. Only 71 of 130 samples were successfully cross-dated, indicating a rather low common signal, a high variability of growth rate between trees and a strong anthropogenic influence at the collection site. The study also showed than the radial growth of *P. flexuosa* is favored by wetter than normal spring precipitation and lower than normal spring temperature. As the species is able to uptake water from the water table, its growth may be more related to water table level fluctuations than directly to rainfall variations.

Preliminary studies at La Salina, in La Pampa, Argentina, indicated that the growth of *Prosopis caldenia* is also controlled by the interannual variations in rainfall. As some individuals of *P. caldenia* reach more than 300 years, there is a high potential to reconstruct some climatic parameters in the Pampas of Argentina using this species (Dussart et al., 1998; Bogino and Villalba, 2008).

In the north-central Chile between 29 and 32°S, Barichivich et al. (2009—this issue) reported the development of tree-ring chronologies using three high elevation species: *Kageneckia angustifolia*, *Proustia cuneifolia* and *Fabiana imbricate*. The chronologies were compared with century-long regional records of precipitation and temperature plus the Niño3.4 Sea Surface Temperature and the Pacific Decadal Oscillation indices. The radial growth of these species is strongly controlled by winter precipitation and is also positively correlated with temperature during most of the rainy season (autumn–spring). Both the regional climate and tree growth is strongly modulated by ENSO and ENSO-like conditions in the equatorial Pacific. The results indicated that these species have very good potential for dendroclimatological studies in the region, extending back 200–250 years.

Recent work in Peru has produced short ENSO-sensitive chronologies from *Bursera graveolens* in the dry forests of northwest Peru (3–7°S; Rodríguez et al., 2005) and from *Prosopis pallida* in the Peruvian Desert between 5 and 14°S (López et al., 2006). Ongoing research is increasing the length of these chronologies, which represent a valuable record for understanding past variations in the tropical Pacific.

4.5. Yungas (21°S–28° 30′S)

Overview: the Yungas forest extends over more than 1500 km along the eastern slopes of the Cordillera de los Andes, from the province of Santa Cruz in Bolivia (18°S) to the provinces of Tucumán and Catamarca in Argentina (28°S). Along the elevational gradient several forest vegetation types occur. The vegetation in the Yunga forest is primarily distributed according to two climatic factors: precipitation, which gradually increases from the east to the west, and temperature, which decreases with elevation. The marked orographic component introduces significant climatic differences within this general regional pattern. Precipitation shows an increase in summer and is the limiting factor controlling the growth of *Cedrela* and *Juglans*. While the climate-growth relations are complex, the two species used in dendrochronology in this area show a noticeable strong precipitation signal. *Juglans australis* (Juglandaceae) is the southernmost species of the genera growing in the region. Its most favorable environment lies between 600 and 1000 m in elevation. However, it grows also as a co-dominant species in forests with *Alnus acuminata* (aliso) and *Podocarpus parlatorei* (pino del cerro), above 1500 m. *Cedrela lilloi* (Meliaceae) grows at mid- to high mountain elevations.

4.5.1. Precipitation

Since the 1980s, distinct, annually formed tree rings have been reported for subtropical montane trees on the eastern slope of the Andes (22–28°S). Chronologies from *Juglans australis* and *Cedrela lilloi* located on the upper tree line (between 1700 and 2000 m) in the montane forest of northwestern Argentina, capture a significant percentage of the variance in regional temperature and precipitation records, and therefore appear as suitable candidates to reconstruct decade-long changes in large-scale circulation over the South American subtropics. In particular, tree growth at xeric sites is strongly influenced by precipitation changes that are modulated by alternating patterns of zonal versus meridional flows over subtropical South America.

Villalba et al. (1992, 1998a,b) studied the spatial patterns of climate and tree-growth anomalies in the montane forests of northwestern Argentina. The tree-ring data set consisted of chronologies developed from *Juglans australis*, and *Cedrela lilloi*. Tree-ring patterns mainly reflected the direct effects of rainfall distribution. Different regression models were used to reconstruct annual and seasonal variations in precipitation (Fig. 6). On average, 60–80% of the variance in regional precipitation was explained using these ring-width chronologies as predictive variables.

The upper tree line records indicate that the increase in precipitation during the past three decades is unprecedented in the past 200 years and appears to be caused by an enhanced transport of humid air masses from the Brazilian–Bolivian lowland tropics to the semiarid subtropics. Although this precipitation increase may reflect natural variability in the subtropics, it is also consistent with 2xCO_2 climatic simulations from five general circulation models (Labraga, 1997). There is a general agreement among model results of a noticeable increase in precipitation in northwestern Argentina. This is due to an intensification of the water transport across subtropical South America in response to a southward displacement of the continental low and an increasing warming at these latitudes.

A chronology from *Schinopsis lorentzii* has recently been developed for the lowland subtropical forest (Parque Chaqueño) in northwestern Argentina (Ferrero and Villalba, 2007). The chronology covers the 1829–2004 period and showed a positive and steady growth during the recent 30 years, proving additional support for the precipitation enhancement in subtropical South America. *Schinopsis* species are widely distributed across the vast semiarid plains shared between Argentina, Bolivia and Paraguay. These very extensive, relatively hot plains play a major role in driving the summer monsoon systems in South America. As a consequence, the *Schinopis* chronology could provide valuable information for understanding past dynamics in monsoon circulation in subtropical South America.

4.5.2. Fire history

At ecotones between the Andean grasslands and the montane forests in northwestern Argentina, Grau and Veblen (2000) used annual tree rings of 265 *Alnus acuminata* trees, the dominant subalpine tree species, to date fire scars, and also determined the

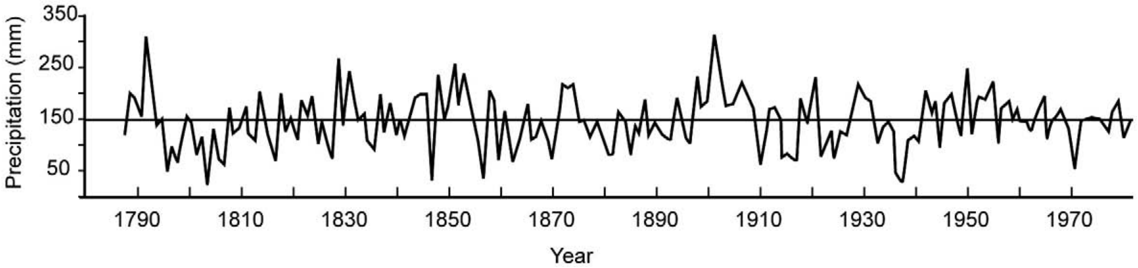


Fig. 6. Reconstruction of July dry season (June to November) precipitation for 1783–1979 based on the four longest chronologies (*Juglans australis*) available from northwestern Argentina (Villalba et al., 1992).

establishment dates of 455 trees that were dispersed over large areas. Fire occurrence during the winter dry season tended to lag by 1 year after years of above-average moisture availability. This pattern is probably due to enhanced production of fine fuels during the growing season of the preceding years. Over 5-year periods, higher fire frequency is associated with greater variability in rainfall. On a 5-year time scale, tree establishment is also associated with higher rainfall variability.

4.6. Tropical regions

Many tropical trees do not have distinct ring structures, or the periodicity of ring-like boundaries is not annual. However, in regions with seasonal rainfall or flooding, several species present clearly visible annual-like rings. In tropical South America, following the pioneer works of Worbes (1985, 1989) and Vetter and Botosso (1989), the number of studies on tree rings in tropical species has increased exponentially as has the list of species with identifiable annual growth rings. However, most of these studies only refer to the presence and periodicity of growth rings (Worbes, 2002; Oliveira, 2007; Oliveira et al., 2009). In this review we focus on studies aimed at the development of chronologies with tropical trees and the establishment of relationships between climate and tree growth.

In the Bolivian Amazon region, Brienen and Zuidema (2005) found six rainforest species that form annual rings and studied the influence of the total amount and seasonal distribution of rainfall on diameter growth. The results of the climate-growth analysis showed a positive relationship between tree growth and rainfall in certain periods of the year, indicating that rainfall plays a major role in tree growth. Three species (*Tachigali vazquezii*, *Amburana cearensis* and *Cedrelinga catenaeformis*) showed a strong relationship with rainfall at the beginning of the rainy season, whereas *Cedrela odorata* was most sensitive to the rainfall at the end of the previous growing season.

The width of the increment zones in the xylem of *Swietenia macrophylla* King and *Cedrela odorata* L. was investigated by Dünisch et al. (2003) using dendroecological methods in a primary forest near Mato Grosso State, Brazil (10°09′S, 59°26′W). Ring-width chronologies for *S. macrophyla* and *C. odorata* were developed from cross-dated increment curves of 33 out of 47 *S. macrophyla* and 51 out of 64 *C. odorata* trees. Simple correlations were computed between the radial growth increment and monthly precipitation for the period 1890–2000. Correlation analyses revealed a significant relationship between the precipitation at the beginning and at the end of the growing season, and the width of the increment zones in the adult xylem of *S. macrophyla*. In contrast, the width of the growth increment in the xylem of *C. odorata* was significantly correlated with the precipitation in March and May of the previous growing season.

According to Dünisch (2005), the ring-width chronology of *Cedrela fissilis* from Mato Grosso State (Brazil), which included 63 out of 87 sampled trees and spanned from 1890 to 2000 (parallel run among trees higher than 90%), presented direct correlation to precipitation ($r = 0.65$; $N = 99$ year) during the second half of the previous growing season (March to May), indicating that shortage in the water supply limits the growing season and influences the formation of food reserves. El Niño events were recorded in the ring-width chronology as lower annual increments, due to reduced precipitation. However, negative growth anomalies also occurred in years not influenced by El Niño, limiting the use of *C. fissilis* chronologies as a proxy for El Niño. There was no association between *C. fissilis* chronologies from Mato Grosso and Paraná (see previous section), which may be explained by different climate triggers in the tropics and subtropics, respectively.

The pluvial regime in the Amazon River basin is characterized by a well-defined intra-annual flood-pulse due to the seasonal precipitation in the Andean watersheds. This phenomenon induces the formation of annual rings in several tree species: cambial dormancy during the flood period is followed by cambial activity during the non-flood period (Worbes, 2002). Ring-width chronologies have been developed for species growing in such seasonally-flooded environments, and related to temporal variation of Amazon River discharges and to El-Niño Southern Oscillation (ENSO) (Schöngart et al., 2004a).

In a related study, Schöngart et al. (2004b) constructed tree-ring chronologies using *Macrolobium acaciifolium* from two floodplain types in Central Amazonia: low elevation nutrient-poor black-water (igapó) and nutrient-rich white-water (várzea). Maximum tree age found in the igapó was more than 500 years whereas ages in the varzea were not older than 200 years. The ring widths in both floodplain forests were significantly correlated with the length of the terrestrial phase (vegetation period) derived from the daily water level records at the port of Manaus since 1903. In both chronologies they found increased growth during El Niño events that cause negative precipitation anomalies and a lower water discharge in Amazonian rivers. The climate signal of La Niña was not evident in the dendroclimatic proxies.

Rigozo et al. (2002, 2004) studied the short- and long-term solar variability that has been suggested to underlie some tree-ring width variations. They used an optical and computational method to obtain a mean ring-width series of *Araucaria angustifolia* from Santa Catarina State in Southern Brazil, covering the period 1797–1996. Spectral analysis was used to identify periodicities using wavelet, maximum entropy and iterative regression methods. The results showed several embedded signals at periods that may be related to solar activity variations. Cross correlation analysis between sunspot number and tree-ring data was performed and a lag of zero years was obtained. From the results, it seems that the tropical conifer species *A. angustifolia* may be a good choice for studies on Sun–Earth relationships and their regional effects.

4.7. Inter-hemispheric studies

Exactly dated tree-ring chronologies along the western coast of the Americas have been used to track climatic variations that have simultaneously impacted the extra-tropical regions of North and South America during the past four centuries. Significantly correlated

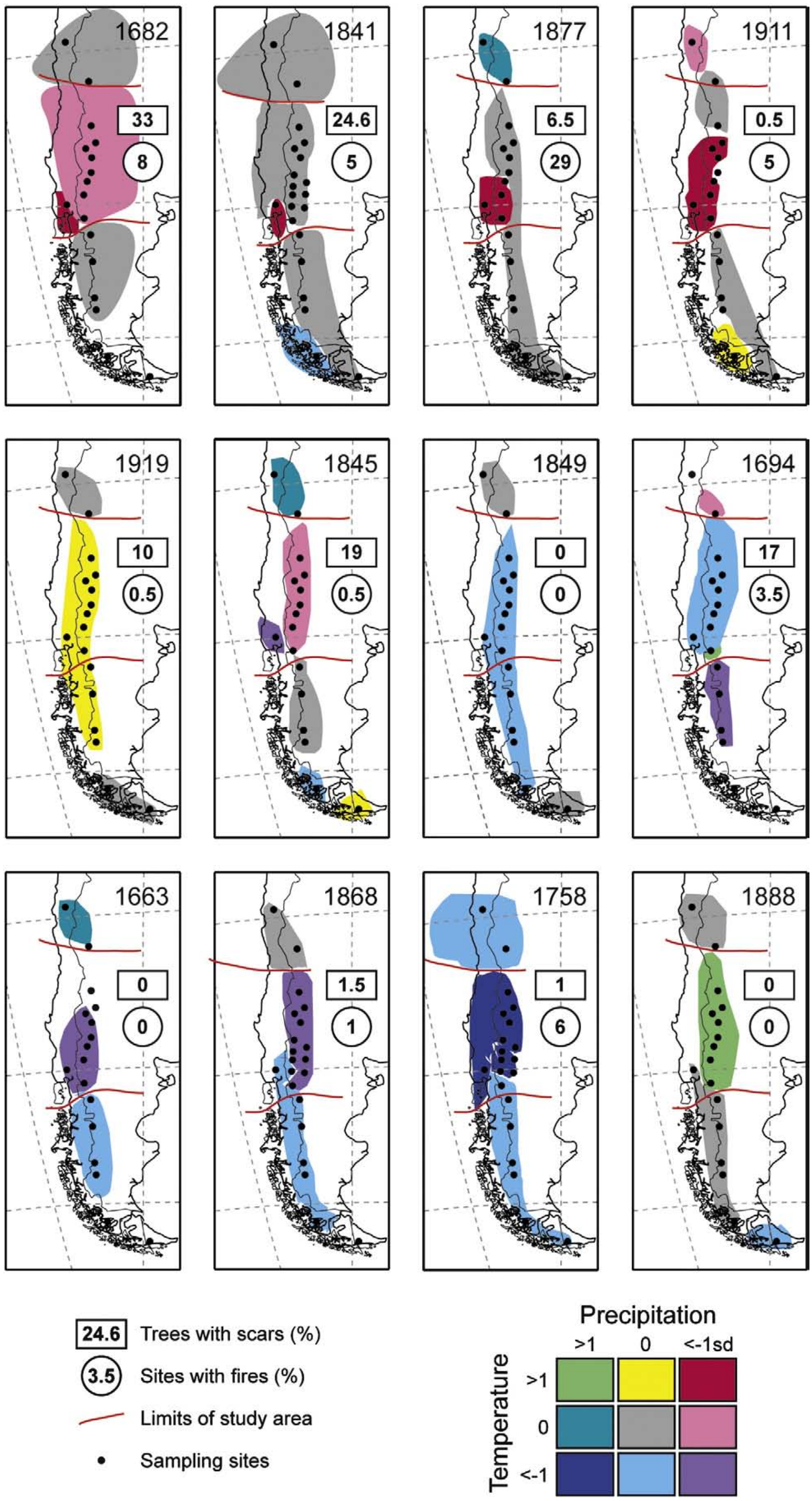
Table 1
The main climatic reconstructions by region, time frame, species and source publications and percent of variance associate with centennial, decadal and intra-decadal oscillations. Numbers in the second column represent the detrending method employed in the development of the chronologies that were used in the respective reconstruction. (1) Double detrending: fitting an exponential curve and then a cubic spline. (2) Fitting only an exponential curve. (3) Detrending using a regional growth curve (Briffa et al., 1992). (4) Fitting only a spline curve of 256 terms.

Area	Climatic/environmental variable reconstructed	Period (length)	Tree species utilized	Source	% variance in waves		
					>100 yrs	99–10 yrs	9.9–2 yrs
South Patagonian Andes	Summer (Nov–Feb) temperature (1)	AD 1750–1984 (235 years)	*Nothofagus pumilio, Nothofagus betuloides*	Boninsegna et al. (1989)	13.26	40.29	46.45
	Minimum annual temperature (2)	AD 1829–1996 (168 years)	*N. pumilio*	Aravena et al. (2002)	39.85	26.69	33.46
	Mean annual temperature (4)	AD 1640–1998 (359 years)	*N. pumilio*	Villalba et al. (2003)	52.81	38.65	8.54
	Summer trans-polar sea-level pressure variability (2)	AD 1700–1995 (296 years)	*N. pumilio*	Villalba et al. (1997b)	6.63	16.82	76.55
	Summer mean sea-level pressure (2)	AD 1746–1984 (239 years)	*N. pumilio, N. betuloides*	D'Arrigo and Villalba (2000)	6.34	23.47	70.19
North Patagonian Andes	Summer (Dec–Mar) temperature (1)	AD 1500–1974 (475 years)	*Araucaria araucana*	Villalba et al. (1989)	3.31	32.67	64.07
	Summer (Dec–Mar) temperature (1)	AD 864–1985 (1122 years)	*Fitzroya cupressoides*	Villalba (1990a,b)	3.56	22.64	73.8
	Summer (Dec–Mar) temperature (1)	1634 BC–AD 1987 (3621 years)	*F. cupressoides*	Lara and Villalba (1993)	0.65	32.6	66.75
	Mean annual temperature (1)	AD 975–1974 (1000 years)	*F. cupressoides*	Villalba et al. (1996)	1.1	57	41.9
	Mean annual temperature (4)	AD 1750–1989 (240 years)	*N. pumilio*	Villalba et al. (1997a)	12.59	14.43	72.97
	Mean annual temperature (3)	AD 1640–1998 (359 years)	*N. pumilio*	Villalba et al. (2003)	47.71	39.46	12.82
	Summer (Dec–Mar) precipitation (1)	AD 1556–1986 (431 years)	*Pilgerodendron uviferum*	Roig and Boninsegna (1992)	2.74	51.74	45.52
	Summer and annual precipitation (2)	AD 1600–1988 (389 years)	*Austrocedrus chilensis*	Villalba et al. (1998a,b)	1.4	67.76	30.34
	Summer (Nov–Dec) precipitation (2)	AD 1837–1996 (160 years)	*N. pumilio*	Lara et al. (2001)	17.46	30	52.47
	Spring snow-cover duration (2)	AD 1750–1984 (235 years)	*N. pumilio*	Villalba et al. (1997a)	11.06	14.88	74.0′6
	Total annual river discharge (1)	AD 1601–1966 (365 years)	*A. chilensis, A. araucana*	Holmes et al. (1979)	no	50.52	49.48
	Summer–fall (Dec–May) river discharge (3)	AD 1599–1999 (400 years)	*P. uviferum, A. chilensis*	Lara et al. (2008)	2.12	40.45	57.44
	Annual precipitation (2)	AD 1600–1949 (350 years)	*A. chilensis*	Schulman (1956)	22.09	40.39	34.12
Central Andes	Winter (May–Oct) precipitation (1)	AD 1220–1971 (752 years)	*A. chilensis*	LaMarche (1975), Boninsegna (1988)	no	20.28	79.89
	Winter (Jun–Dec) precipitation (3)	AD 1310–2000	*A. chilensis*	Le Quesne et al. (2009-this issue)	11.76	24.98	63.52
	Anticyclone position (1)	AD 1497–1974 (478 years)	*Several*	Villalba (1990a,b)	0.92	18.13	80.96
	Streamflow (1)	AD 1575–1983 (690 years)	*A. chilensis*	Cobos and Boninsegna (1983)	no	50.52	49.48
Yungas	Annual and seasonal precipitation (2)	AD 1814–1994 (181 years)	*Juglans australis* *Cedrela lillio*	Villalba et al. (1992, 1998a,b)	48.58	17.82	76.55

records for the coast of Alaska and northern Patagonia showed the existence of common oscillatory modes for temperature variations at 9, 13 and 50 years in both regions. Tree-ring chronologies from precipitation-sensitive regions also revealed the occurrence of decadal-scale oscillations centered at 8 and 10–18 years, which simultaneously influence climatic conditions in the Midwest–Southern United States and central Chile. The spectral decomposition of these tree-ring series suggests the existence of decadal-scale oscillations common to the climates of western North and South America, while the spatial correlation patterns between tree-ring records and Central Pacific SSTs indicate that the Pacific Ocean is the major forcing driver for this synchronous oscillation (Villalba et al., 2001).

Fire histories were compared between the south-western United States and northern Patagonia, Argentina, using documentary records and tree-ring reconstructions over the past several centuries. The two regions share a similar relationship of climatic anomalies with the El Niño–Southern Oscillation (ENSO). Major fire years tend to follow the switching from wet-El Niño years to dry-La Niña conditions. The inter-hemispheric synchrony of fire regimes in these two distant regions is tentatively interpreted to be a response to decadal-scale changes in ENSO activity. The ENSO–fire relationships of the south-western USA and northern Patagonia document the importance of high-frequency climatic variation to fire hazard. Thus, in addition to long-term trends in mean climatic conditions, multi-decadal scale changes in year-to-year variability need to be considered in assessments of the potential influence of climatic change on fire regimes (Kitzberger et al., 2001).

The effects of volcanic eruptions that inject important quantities of aerosols to the upper atmosphere on tree growth in South America has been estimated by Villalba and Boninsegna (1992) and Boninsegna and Hughes (2001). No significant signal of volcanic explosions has been demonstrated in South American chronologies or the temperature reconstructions derived from them. The authors concluded that the strong oceanic influences on South America climate temper the impact of the volcanic eruptions on regional climates.


1682
33
8
1841
24.6
5
1877
6.5
29
1911
0.5
5
1919
10
0.5
1845
19
0.5
1849
0
0
1694
17
3.5
1663
0
0
1868
1.5
1
1758
1
6
1888
0
0
24.6 Trees with scars (%)
3.5 Sites with fires (%)
Limits of study area
Sampling sites
Precipitation
>1
0
<-1sd
Temperature
>1
0
<-1

5. Discussion

Chronology development in South America has followed the standard methods recommended by the International Tree Ring Data Bank, especially in cross-dating quality control. The standardization procedures have varied broadly, from studies that filter out the low frequency wavelengths to more conservative strategies that retain a major proportion of the low frequency variance in the tree-ring series. Table 1 lists the available tree-ring based climate reconstructions using South American chronologies and the percent of variance associated with centennial (>100-year period), interdecadal (99.9 to 10.0-year period) and interannual (9.9 to 2.0 years) bands in each reconstruction. It is interesting to note that earlier reconstructions preserve, in general, a lower percentage of low frequency associate variance due to the standardization techniques used during the 1980s and early 1990s. The reconstructions more recently developed, which used more conservative approaches in series standardization, show a large amount of variance associated with low frequencies.

The study of spatial patterns of climate variation along the Andes is a pending challenge in South American dendrochronology. Different species have different climatic sensitivity, and even the same species shows differences in response according to its location along environmental gradients. In future research, the search for a homogeneous network of chronologies with similar climatic responses must be encouraged to enhance the common climatic signal between records.

Reconstructions of temperature, rainfall, streamflow, snow, and atmospheric circulation features (STPI, high-pressure cell fluctuations) have been carried out using tree rings from subtropical and temperate regions in South America. These chronologies were also used in studies relating South American tree-ring proxies to high-resolution proxies of other continents, in studies of aspects of the atmospheric general circulation and, in particular, in studies of atmospheric (ENSO, PDO and AAO) and solar forcing. The comparison of climatic reconstructions based on tree rings with projected atmospheric circulation patterns is providing useful bridges between the past and future trends in global climate change and the implications for human welfare and socio-economic development. A good example of this bridging is the decrease in the Puelo River summer–fall streamflow related to the increase in the Antarctic Oscillation (AAO; Lara et al., 2008). It has been suggested that both Antarctic ozone depletion and increasing greenhouses gases have contributed to the positive trend on the AAO during the past decades (Gillett and Thompson, 2003). These projected changes in atmospheric circulation would reduce summer–fall precipitation in the Puelo River basin, potentially increasing the likelihood of persistent and more severe droughts, and thus periods of reduced streamflows. The decreasing trend in the summer–fall streamflow of Puelo River since the 1980s, as part of its long-term cyclical variation, determines constraints in the future economic development of the region. Salinity and the dissolved oxygen in the Reloncavi Estuary are the main limiting factors of the farmed salmon industry in this area, and both depend on Puelo River streamflow, especially during the fall. In addition, limitations to the future economic development of the area will be stressed by the construction in the Puelo basin of a 1250-mW/h hydroelectric generation system (one of the largest in Chile) in the next years. Planning for the future economic development of the area should consider the decreasing trends of the summer Puelo River streamflow in response to current and projected atmospheric circulation changes (Urrutia et al., 2005).

The analyses of the return intervals between droughts in the instrumental and reconstructed precipitation series of Santiago de Chile indicate that the probability of drought has increased dramatically during the late 19th and 20th centuries, consistent with selected long instrumental precipitation records and with the general recession of glaciers in the Andean Cordillera. This increased drought risk has occurred along with growing demand on surface water resources and may heighten socio-economic sensitivity to climate variability in central Chile (Le Quesne et al., 2006).

The South American climate reconstructions and other proxy data have been used to establish relationships between climate and other phenomena, in particular glacier fluctuations, fire history and frequency of insect outbreaks. Fig. 7 is an example of the combined use of climatic reconstructions and fire occurrence. It shows those years in which annual precipitation and/or temperatures are greater than one standard deviation from the long-term mean in northern Patagonia, in addition to the evidence for fires in the region. A high coincidence is observed between dry and hot years with increased incidence of fires.

Since fire is a major ecosystem disturbance across the Andes, research on the links between fire regimes and interannual and decadal-scale climate variability should be stressed; enhancing and broadening the studies already completed or in progress. A network of fire histories would provide a better understanding of the effects of climate variability and seasonality on fire regimes in different ecosystems along the major environmental gradients.

Studies on the integration of tree-ring and stratigraphic records (pollen, charcoal and tephras from lake sediments and peat bogs) to decipher the patterns, rates and directions of vegetation, climate change and fire regimes have just started to emerge in South America. For example, studies integrating high-resolution pollen and charcoal records with tree rings in the Chonos Archipelagoes (44°20′ S) for the reconstruction of environmental changes at different resolutions, have achieved promising results (Szeicz et al., 2003). Research using *Fitzroya* tree rings from subfossil wood yielded a floating chronology that was radiocarbon dated to >50,000 ^{14}C year BP (Roig et al., 2001), indicating a potential for the integration of records into the Pleistocene and stressing the importance of subfossil wood as proxy archives. Multi-proxy approaches require a considerable amount of effort, collaboration and funding, but provide a unique opportunity to improve the understanding of the long-term spatial and temporal patterns of climate, fire and volcanism, and should therefore be given high priority (Lara et al., 2005c).

The development of chronologies using species from arid tropical and subtropical regions of the Cordillera and, in particular, the Altiplano, is probably one of the most important advances in the recent history of the South American dendrochronology. *Polylepis tarapacana* has yielded several chronologies of significant length with a strong climatic signal. The development of tree-ring chronologies in these vast subtropical areas should include new species and sites and must also be regarded as a high research priority. These studies will document precipitation patterns, providing critical information for a better understanding of ENSO, and the influence of the Easterlies and Atlantic Ocean SST in the subtropical climate of South America.

The development of chronologies in humid subtropical or tropical climates remains a major challenge. Tree-ring visualization, circular uniformity and cross-dating are the main problems in developing tropical chronologies. Despite obvious advances in the last decades, the number of tree-ring chronologies built up using species growing in those regions is rather low. However, these chronologies have been useful for studies of climate-growth relationships, ENSO effects and solar forcing. In particular, the identification of strong climate signals

Fig. 7. Reconstructed patterns of spatial climate variability for selected years in southern South America. Years with anomalies exceeding ± 1 standard deviations from mean reconstructed temperature and/or precipitation in Northern Patagonia were chosen. Due to the lack of temperature reconstructions for Central Andes and of precipitation reconstructions for South Patagonia, mean climatic conditions were assumed. Values in boxes (upper) and circles (lower) refer to the mean number of trees with fire scars and the percent of sites with fire signals, respectively.

in tree rings of *Cedrela* species provides a great opportunity to develop a wide tree-ring network in subtropical and tropical South America. The future of dendroclimatology in the region is perceived as extremely promising. A high priority should be given to this kind of research due to the increasing human impact on the area, which threaten the existence of vast forest areas and consequently imply the irreversible loss of these proxy archives.

Finally, no specific studies have been carried out on the divergence problem due to changes in the tree response to climatic factors in a higher atmospheric CO_2 concentration. This issue, which has recently been reported in several regions around the world, needs to be carefully evaluated in the dendrochronological records from South America.

6. Conclusions

The current network of dendroclimatic records and reconstructions available in South America, provide a good starting point for the preliminary analyses of year-to-year variations of past climates in space and time domains. Whereas the spatial coverage of the chronologies is still limited, some features are emerging in terms of common climatic episodes of local, regional or continental scales. As examples, warm periods visualized in the longest temperature reconstructions from South America are not always coincident with the Medieval Warm Period identified in the North Atlantic domain. Although cold phases synchronous with the “classic European” Little Ice Age are recorded in some areas, significant differences in the temporal occurrence of the cold periods emerge between regions. The most consistent pattern recorded at most sites is the occurrence of warmer conditions in the 20th century in comparison with previous centuries.

The long-term impact of ocean-atmosphere (ENSO, PDO and AAO) and solar modes of variability on South America climate and related phenomena such as fire occurrences, floods and forest infestations, are also emerging in several regions. However, South American dendroclimatology still requires a comprehensive amount of work to produce regional pictures of climate variations and their connections at the sub-continental scale. This is a challenge that needs to be tackled in the near future.

Further, future research should address the continuing development of long tree-ring chronologies to improve detection of decadal to centennial signals in climatic variations, and to distinguish between natural and human-induced climatic changes. Reconstructing long-term streamflow as a basis for predicting future trends and their possible economic impacts should also receive high priority, since water availability is a key factor in future development throughout the Andes. Irrigation, hydroelectricity, industry and tourism are major economic activities, which strongly depend on water availability (Lara et al., 2005c, 2008).

Collaboration between researchers along the South American Andes, including, Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Perú and Venezuela, as well as training of young scholars, is crucial to make effective progress in the study of climate change in the region. Initiatives such as the IAI Collaborative Research Networks, which facilitate the interactions between scientists from the Americas, should be broadened and their long-term continuation assured. High-quality paleoclimate datasets covering a wide geographic area in the Americas, developed through a focused and effective collaboration, can be used to validate global climate models (GCMs). Such analysis has the potential to achieve major breakthroughs in the improvement of the resolution and quality of GCMs, as well as in the understanding of global change patterns and mechanisms. The improved predictive capacity of climate models is relevant to the planning of natural resource management as well as for policy making.

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