Climate Fluctuations Derived from Tree-rings and Other Proxy-records in the Chilean Andes: State of the Art and Future Prospects

Antonio Lara[1*], Alexia Wolodarsky-Franke[1], Juan Carlos Aravena[2], Ricardo Villalba[3], Maria Eugenia Solari[4], Liliana Pezoa[1] , Andrés Rivera[5], and Carlos Le Quesne[1]

[1]*Instituto de Silvicultura, Facultad de Ciencias Forestales, Universidad Austral de Chile, Casilla 567, Valdivia, Chile*

[2]*Centro de Estudios Cuaternarios, Universidad de Magallanes - Department of Geography, University of Western Ontario*

[3]*Departemento de Dendrocronología e Historia Ambiental, IANIGLA, Mendoza, Argentina*

[4]*Instituto de Ciencias Sociales, Universidad Austral de Chile*

[5]*Departamento de Geografía, Universidad de Chile - School of Geographical Sciences, University of Bristol*

**phone ++56 63 221228, 226302, fax ++56 63 221230, email alara@uach.cl*

Keywords: Andes, Climate fluctuations, Glacier fluctuations, Patagonia, Proxy-records, Tree-ring

1. Introduction

Treeline and high elevation sites in the central and southern Chilean Andes (32°39’ to 55°S) have shown to be an excellent source of paleoenvironmental records because their physical and biological systems are highly sensitive to climatic and environmental variations. In addition, most of these sites have been less disturbed by logging and other human induced disturbances, which enhances the climatic signals present in the proxy records (Luckman 1990; Villalba et al. 1997).

Current studies on tree-ring, glacier and documentary records in the Chilean Andes have led to important progress in the understanding of climate fluctuations in the last 1000 years against which current changes can be assessed. The integration of these proxies provides an opportunity to study climatic signals across a wide range of spatial and temporal scales. In this contribution, we discuss the state of the art in the reconstruction of climate variability from tree-rings and other proxy records in three main regions along the Chilean Andes: the Central Andes (32°40'-39°S), Northern Patagonia (39°-48°S) and Southern Patagonia (48°-55°S). We also discuss future needs and challenges for global change research in the Chilean mountain ranges.

2. Research in Chilean mountain environments: Progress and gaps

Tree-ring studies at high elevation sites have produced a network of tree-ring chronologies, covering a 2530 km latitudinal gradient in the Chilean Andes (Fig. 1). This research has rendered important progress in the understanding of climate and environmental fluctuations on inter-annual to century timescales and of the potential mechanisms behind this variability.

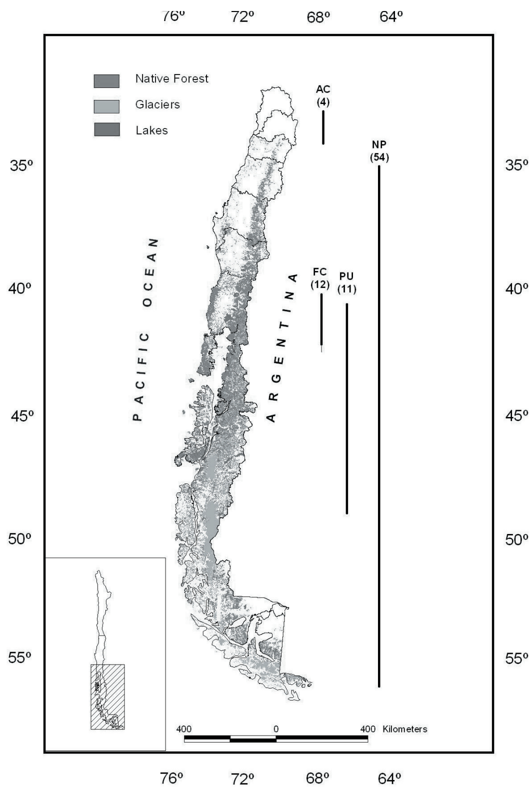

Figure 1: Map showing the latitudinal distribution of tree-ring chronologies for different native species. AC: *Austrocedrus chilensis*; NP: *Nothofagus pumilio*; FC: *Fitzroya cupressoides*; PU: *Pilgerodendron uvifera*. The numbers in brackets indicate the number of existing chronologies for each species in Chile.

2.1 Central Andes (32°40'- 39°S)

This region has a climate of Mediterranean type. Rain and snow are concentrated in fall and winter, when over 75% of the annual precipitation occurs, with a north to south increase in rainfall. There is also an important west-east moisture gradient, with a distinct rainshadow effect east of the highest Andean peaks. Interannual climate variability is mainly driven by El Niño-Southern Oscillation (ENSO) events and the changes in the intensity and latitudinal position of the Southeast Pacific anticyclone (Miller 1976).

In the northernmost portion of the Central Chilean Andes (32°40'-35°40'S), the long-lived conifer *Austrocedrus chilensis* has been used for dendroclimatic studies. These moisture-limited sites yielded a precipitation reconstruction for the last 1000 years. *Austrocedrus* growth is positively related to winter precipitation, and one of the main features of the reconstruction are two long periods of droughts, one between AD 1270-1450, and the other between AD 1600-1650 (LaMarche et al. 1979; Boninsegna 1988). Instrumental precipitation records between 33° and 36° S show no increasing or decreasing trend in precipitation (Pezoa 2003) for the 1931-2001 period. Interannual precipitation variability is high with a variation coefficient ranging between 41% and 43% for most stations (Pezoa 2003). Although temperature reconstructions from tree-rings have not been developed for this region, instrumental records between 33° and 36° S show a steady increase in mean annual temperatures for the period 1965-2001 (Pezoa 2003).

Dendroclimatic research has also been conducted in the northernmost portion of the deciduous *Nothofagus pumilio* forests at upper treeline and high elevation sites (1500-1720 m asl), ranging from 35°37' to 37°30' S. Here, eight tree-ring chronologies have been developed. Results indicate a positive correlation of tree-ring width with late-spring and early-summer precipitation and a negative correlation with temperature (Lara et al. 2001). In this region, high temperatures in spring and summer, which enhance evapotranspiration and decrease water availability, appear to reduce radial growth. In contrast, at wetter high elevation sites located further south (38°37' S), radial growth is negatively correlated with late-spring and early-summer precipitation. From this set of chronologies, a reconstruction of November-December precipitation, accounting for 37% of the instrumentally recorded precipitation variance, was produced (Fig. 2a). This reconstruction shows that the twentieth century has the most extreme intervals of both summer drought and wetness since 1837, and that the driest and wettest 25-year periods are 1890-1914 and 1917-1941, respectively (Fig. 2a; Lara et al. 2001).

Progress has also been made in the inventory of glaciers and the analysis of their fluctuations in relation to regional climate change (Rivera et al. 2000). Studies based on the interpretation of aerial photographs show a general glacier retreat in the Central Andes (Rivera et al. 2000). A local study at Los Cipreses Glacier (34° 33') based on historical documents, sketches and maps shows an average retreat of 10 m/year between 1858-1888, which increases to 30 m/year for 1888-1968 (Le Quesne and Acuña 2003).

Despite the progress in tree-ring studies, there is an important geographic gap in the area north of the Central Andes, ranging from 17°40' to 32°40' S. This gap includes the Chilean *Altiplano,* from 19° to 22° S (the high Andean plateau shared between Perú, Bolivia, Argentina, and Chile), and the region located between 22° and 32° 40' S. Filling this gap is a priority, and currently we are working on the development of tree-ring chronologies of *Polylepis tarapacana*, collected from 20 sites located at 4151-4781 m asl, along its entire latitudinal range in Chile (17°40'-21°20'). Research in the adjacent Bolivian and Argentinean Altiplano has rendered four chronologies, the longest starting in AD 1297 (Argollo et al. 2003). The chronologies located between 18° and 22° S show a strong positive correlation with summer precipitation (Soliz et al. 2003; Argollo et al. in preparation). Further south, between 21° and 33° S, the potential for dendroclimatological studies of *Prosopis spp*. and other species growing in scattered populations through a vast desert region should be investigated to fill the remaining gap spanning 1400 km between the *Polylepis* and the *Austrocedrus* populations in Chile. Sample collection of *Prosopis chilensis* at various sites in northern Chile started in 2003. A tree-ring chronology of *Prosopis ferox* has been developed in northwestern Argentina, indicating high dendroclimatic potential for this species distributed between 20° and 25° S in Bolivia and Argentina, reaching 240-280 km west of the border with Chile (Morales et al. 2001). This chronology, developed for a site at 3500 m asl, has a positive correlation with precipitation and a negative correlation with temperature, interpreted as a positive response to soil water availability.

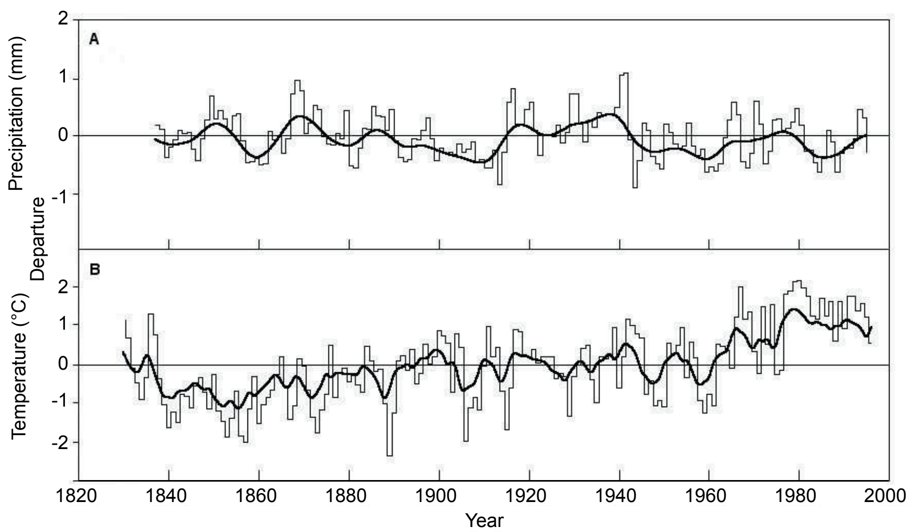

Figure 2: A) Tree-ring based reconstruction of November-December precipitation for the Central Andes of Chile (35°-39°S) from 1837 to 1995. A trend line drawn to emphasize the low-frequency variation was obtained using a cubic spline (Cook and Peters 1981). B) Tree-ring based reconstruction of minimum annual temperature for Chilean Southern Patagonia from 1829 to 1996. A trend line drawn to emphasize the low-frequency variation was obtained using an exponential filter (Essenwanger 1986).

2.2 Northern Patagonia (39°-48° S)

South of 39°S, strong westerlies are remarkably persistent throughout the year, occurring at least 75% of the time along the entire coast. Temperature patterns are strongly influenced by latitude and elevation. The increasing influence of the westerlies is reflected in more abundant rainfall and a reduced summer season towards the south. Precipitation over the Andes increases with elevation, reaching a maximum close to the crest of the range. Precipitation is closely related to the north-south seasonal shifts of the Southeastern Pacific anticyclone. In northern Patagonia, warm El Niño events are generally associated with cooler/wetter winter-springs and warmer/drier summers, whereas most La Niña events correspond to warmer/drier winter-springs and cooler/wetter summers (Villalba et al. 2003).

Dendroclimatological research has been quite extensive in this region, using *Fitzroya cupressoides* and *Nothofagus pumilio,* and to a lesser extent *Pilgerodendron uvifera*. These studies have produced a network of 23 tree-ring chronologies for *Fitzroya* (40°10' to 43°30' S), both in Chile and Argentina, 19 of which are >1000-year long (Lara et al. 2000), and recently a 5666-year long chronology has been generated (Wolodarsky-Franke 2002). Based on the significant negative correlation between *Fitzroya* tree-ring widths and previous summer (December to March) mean temperatures, a 3622-year temperature reconstruction was developed (Lara and Villalba 1993). The longest period of slow growth, and therefore above-mean reconstructed temperatures, in this chronology was from 80 BC to AD 160. Current research is analyzing this period in more detail, using tree-ring records from other sites, as well as lake sediments and pollen records for a multi-proxy approach.

Growth patterns and climatic response of *Pilgerodendron uvifera*, reconstructed from a network of nine chronologies situated between 39°36' and 49°15' S, have been studied (Szeics et al. 2000). Sites located in the southern portion of this range show a strong negative response to summer temperatures. Conversely, a positive response to summer and annual temperatures is reported for two sites at or near treeline in the Coastal Archipelagoes (46°10', 700 m asl). A marked increase in tree-growth since the mid-20th century, attributed to an increase in mean annual temperature in this period, is reported (Szeics et al. 2000). However, none of the other *Pilgerodendron* sites show evidence of a warming trend during the 20th century, following a similar pattern as the one described for the 3,622-year temperature reconstruction from *Fitzroya* tree-rings (Lara and Villalba 1993).

Recent studies of instrumental records in the Southern Andes of Argentina and Chile report a negative trend in mean annual temperature with a marked cooling period from 1950 to 1975 in the region between 37° and 43° S (Rosenblüth et al. 1997; Pezoa 2003; Villalba et al. 2003). This is described as one of the main regional patterns in the Southern Andes from 37°-56° S (Villalba et al. 2003). The second dominant pattern, which followed this cooling trend, is a pronounced and widespread increase of temperatures starting in 1976 in both the Chilean and Argentinean North Patagonian Andes (Villalba et al. 2003).

Temperature reconstructions from composite tree-ring chronologies across Northern and Southern Patagonia in both Chile and Argentina, using standardization methods to preserve low-frequency (decadal to centennial) variations have been recently accomplished (Villalba et al. 2003). This study indicates that temperatures during the 20th century have been anomalously warm across northern and southern Patagonia in both Argentina and Chile (37°-55° S), compared to the reconstructed temperatures for the past 360 years (Villalba et al. 2003). These reconstructions show a well-defined cold period from 1640-1850, which is roughly synchronous with the "Little Ice Age" in both Hemispheres (Villalba et al. 2003). The warming trend during the 20th century is distinguishable, despite the cooling trend from 1950-1975, observed between 37°-43° S. The increase in temperature since 1976 is most evident in summer and may be associated with a shift in the Pacific Decadal Oscillation (PDO) at that time (Graham 1994). Sea Surface Temperature (SST) anomalies associated with this decadal mode reached into mid-latitudes in both hemispheres. Long-term dominant modes of atmospheric circulation in the Southern Hemisphere are connected to global changes in SST (Mo 2000). The 20th century increase in temperatures for the Southern Andes is the local atmospheric response to large-scale ocean-atmosphere changes (Villalba et al. 2003).

Most glaciers are retreating in Northern Patagonia and the reduction of ice-masses that have accumulated over preceding centuries has continued (or accelerated) to the present. Studies based on the interpretation of air photos and satellite images indicate that land-based glaciers and most calving glaciers in the Northern and Southern Patagonian Icefields have retreated since 1945, in some cases at an increasing rate (Naruse and Aniya 1992; Cassasa et al. 2002; Rivera et al. 2000; 2002).

Climatic reconstructions using historical records are in progress for the area located between 39° to 41° S. These records include documents, maps and sketches prepared by travelers and surveyors. Data are more abundant after 1850 and the first photographs were taken in 1901. These records also show a steady and distinct glacier retreat through present. A general glacial retreat in Northern Chilean Patagonia is probably the result not only of increased temperatures since 1850, but also of a regional decrease in precipitation registered at least since 1931 (Rosenblüth et al. 1995). The steady precipitation decrease in the 1931-2001 period, recorded at most of the weather stations between 37° and 45° S, is the dominant regional precipitation pattern (Pezoa 2003).

2.3 Southern Patagonia (48° to 55° S)

The climate of southern Chilean Patagonia is characterized by a dramatic decrease in precipitation and humidity from west to east. In southernmost Patagonia, this gradient shifts from a west to east orientation to a south-west to north-east pattern, following the dominant position of the Andean range (Aravena et al. 2002). Annual rainfall ranges from 8000 mm in the western archipelagoes to 250 mm and less on the plateau east of the Andes. Precipitation is mainly affected by the influence of the strong and persistent westerly winds, which dominate the whole region throughout the year, and there is almost no seasonality in precipitation distribution (Carrasco et al. 1998).

Nothofagus pumilio tree-ring growth studied at 21 high elevation and upper treeline sites (500-980 m asl) in southern Chilean Patagonia shows a significant positive correlation with summer temperature (December-January) of the current growing season at most sites (Aravena et al. 2002). Some sites show a significant positive correlation between tree growth and fall-early winter temperature of the previous season. In addition to this temperature response, most chronologies located towards the southern limit of *N. pumilio* on Navarino Island (55° S) have a negative correlation with precipitation (Aravena et al. 2002). Tree-growth may be negatively affected by more extended snowfall seasons and snow accumulation through the spring, associated with higher precipitation years at these relatively cooler and wetter southern sites. This effect has also been described for the Argentinean portion of Northern Patagonia at 41° S (Villalba et al. 1997).

The significant correlation between *N. pumilio* tree-ring widths and temperature allowed the reconstruction of minimum annual temperature fluctuations since 1829 (Fig. 2b; Aravena et al. 2002). During most of the 19th century, minimum annual temperatures remained below average and increased to values fluctuating around the mean during the period 1900-1960, followed by a clear trend towards above-average values after 1963 (Fig. 2b). This warming trend since 1963 coincides with the patterns described from instrumental records for the extreme south of South America (45°-55° S), but contrasts with the cooling trend between 1950 and 1975 for Northern Patagonia (37°-43° S), described above (Rosenblüth et al. 1997; Villalba et al. 2003). Precipitation patterns from the only two available weather stations in Southern Chilean Patagonia show a steep increase since 1983 for Faro Evangelistas, located at 52°24' S at the western fringe of the Archipelagoes, and a slighter increase for Punta Arenas (53° S) between 1983 and 2001, following two decades of below-mean precipitation (Carrasco et al. 2002; Pezoa 2003). This recent precipitation increase is in contrast to the dominant pattern described for Northern Patagonia.

Glaciers in the Southern Patagonian Icefield show a substantial and rapid retreat, following the pattern described for the Central and North Patagonian Andes (Naruse and Aniya 1992; Cassasa et al 2002; Rivera et al. 2002). Pío XI Glacier is an exception to this general trend, showing a distinct advance due to local ice dynamic factors (Rivera et al. 1997). Current estimates indicate that the general retreat observed in the Southern Patagonian Icefield accounts for 6% of the global sea level rise (1-2 mm/year during the last 100 years; Rivera et al. 2002).

Historical documents for the Magellan region (50°-56° S) date to the time of its discovery by Europeans in 1520 and historical sources exist since then (Prieto and Herrera 1998). These data indicate a cold period between 1520 and 1670, synchronous with a cold interval identified by tree ring records (Villalba 1994). Photographs taken by Agostini (mainly in Southern Patagonia in 1923, 1945, 1949 and 1955) show a general retreat of glaciers during the 20th century (Solari et al. 2003).

3. Future needs and challenges for global change research in the Chilean mountain ranges

Research in the Chilean Andes (latitudes 32°40'-55° S), using tree-rings and other climate proxy records, has demonstrated a high potential for understanding the environmental and climate variability of the last millennia in this region. Instrumental records, as well as proxy-records from tree-rings, glaciers and historical documents, show a consistent increase in temperature during the 20th century, compared to the previous 360 years. This warming trend documented for the Chilean and Argentinean Andes (37°-55° S) is a response to large-scale ocean-atmosphere changes expressed in increasing Sea Surface Temperature (SST) of the Southern Pacific and Atlantic Oceans (Villalba et al. 2003; Villalba et al., this volume). Further research on the relationships between SST and atmospheric temperatures over southern South America will improve our knowledge of global change mechanisms and responses in this region.

A warming trend in the Central Andes since 1858 is evident from glacier records and is a dominant pattern at least since 1965 based on instrumental records located between 33° and 36° S. This 20th century warming trend is also clear in Southern Patagonia, as indicated by tree-ring, glacier and instrumental records. Conversely, in Northern Patagonia a cool period between 1950 and 1975 is a dominant feature, and some tree-ring records do not show a temperature increase in recent decades. Nevertheless, glaciers show a strong retreat in Northern Patagonia during the 20th century. Glacier records give a good estimate of overall temperature and/or precipitation changes from one century to the next (Luckman and Villalba 2001). In contrast, tree-rings generally show a relatively strong inter-annual climatic signal, as well as a decadal or centennial signal of variable strength, depending on species, site, length of the individual tree-ring series and standardization methods (Briffa et al. 1996). These differences between climatic responses probably explain the discrepancies between the glacier records and some of the tree-ring records in Northern Patagonia. In Southern Patagonia, the scarcity of instrumental records between 46° to 55° S, in a vast and climatically highly variable area, is a limitation for understanding temperature and precipitation patterns.

Future research should address these and other limitations to improve our knowledge of the long-term spatial and temporal patterns of climatic variability on both the western and the eastern slopes of the Andes. A main objective of future research in mountain areas in Chile should be to continue the development of millennial tree-ring chronologies of long-lived native species, such as *Fitzroya cupressoides, Austrocedrus chilensis, Pilgerodendron uvifera,* and *Araucaria araucana,* to detect decadal to centennial signals in climatic variations and to distinguish between natural and human-induced climatic changes. Since *Pilgerodendron uvifera* is the only conifer growing between 43°30' and 54° S, which shows both a temperature and precipitation signal, future research on this species seems promising. Streamflow reconstructions in Northern Patagonia using *Pilgerodendron* tree-rings are in progress (Urrutia et al. 2003). These types of studies are needed for a better understanding of the hydrological response to the observed precipitation decrease in Northern Patagonia and the widespread temperature increase throughout the Andes. Reconstructing long-term streamflow as a basis for predicting future trends and their possible economic impacts should receive high priority, since water availability is a key factor for future development throughout the Andes. Hydroelectricity, fish farms, sports fishing and tourism are major economic activities, which strongly depend on water availability (Urrutia et al. 2003).

The development of tree-ring chronologies for the Northern Chilean Andes (17°40'-32°40'), which has already been started for *Polylepis tarapacana* and *Prosopis chilensis,* should include new species and sites and must also be regarded as a high research priority. These studies will document precipitation patterns in this vast subtropical area, providing critical information for a better understanding of ENSO, the influence of the Easterlies, and changes in SST of the Atlantic Ocean.

Since fire is one of the main disturbances throughout the Chilean Andes, research on the links between fire regimes and inter-annual and decadal scale climate variability should be stressed, enhancing and broadening the studies already completed or in progress in *Austrocedrus, Fitzroya* and *Araucaria* forests (Lara et al. 1999; 2003; González 2002; Aravena et al. 2003). 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. The study of the climatic and ecological effects of volcanism reconstructed from tree-rings is also a relevant topic. Research on the increase in interannual climate variability and its influence on forest dynamics (e.g. tree mortality, seedling establishment, fires ignited by increased lightning occurrence) should be developed in Chile, complementing research in Northern Argentinean Patagonia in *Austrocedrus* and *Nothofagus dombeyi* habitats (Villalba et al., this volume).

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 changes in vegetation, climate and fire regimes since the Last Glacial Maximum (c. 17,000 years B.P.) have started. A recent study integrates high-resolution pollen and charcoal records from small lakes with *Pilgerodendron* tree-rings in the Chonos Archipelago (44°20' S, Szeicz et al. 2003). This reconstruction of the impacts of climate change and fire on vegetation shows promising results. Research using *Fitzroya* tree-rings from sub-fossil wood yielded a floating chronology that was radiocarbon dated to 50,000 ^{14}C yr B.P. (Roig et al. 2000), indicating a potential for the integration of records into the Pleistocene. 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 therefore should be given a high priority.

Collaboration between researchers along the South American Andes, including Perú, Bolivia, Argentina, and Chile, as well as training of young scholars, is crucial to make effective progress in the study of climate change in the region. An ongoing collaborative research initiative on climate variability in the Americas from treeline environments (CRN03 project of the Inter American Institute for Global Change Research, IAI) is making a significant contribution to our understanding of large-scale climate change mechanisms along a transect spanning from Alaska to Tierra del Fuego. Such initiatives should be broadened in geographic range and their long-term continuation should be assured. High quality datasets from paleo-climate records 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 studies have 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.

4. Acknowledgements

This review is largely based on research supported by FONDECYT Projects 1000445, 1010200, and 1030766, the CRN03 project of the Inter American Institute for Global Change Research IAI, and Mideplan, through its Iniciativa Cientifica Milenio (ICM). We thank Museo Histórico-Antropológico U. Austral (Valdivia), Museo Salesiano (Punta Arenas), Club Andino Alemán (Santiago) and the Ministerio de Obras Públicas (Santiago) for providing historical and photographic records. Dirección Meteorológica de Chile contributed with the temperature and precipitation records. E. Neira and P. Romero drew the figures. A. Lara acknowledges support from a Bullard Fellowship from the Harvard Forest (Harvard University). We are grateful to the editors for the invitation to contribute with this chapter and for their careful review of earlier versions of our paper.

5. References

Aravena, J. C., Lara, A., Wolodarsky-Franke, A., Villalba, R., and Cuq, E. (2002). Tree-ring growth patterns and temperature reconstruction from *Nothofagus pumilio* (Fagaceae) forests at the upper tree line of southern Chilean Patagonia. *Revista Chilena de Historia Natural* **75**, 361-376.

Aravena, J.C., LeQuesne, C., Jiménez, H., Lara, A., and Armesto, J. J. (2003). Fire history in central Chile: tree ring and modern records. *In* "Fire and climatic change in temperate ecosystems of the Western Americas." (T. T. Veblen, T. Swetnam, and G. Montenegro, Eds.), pp. 343-356. Springer, New York.

Argollo, J., Soliz, C., Villalba, R., and Montevilla, J. (2003). Dendrochronology and dendroclimatology in Bolivia. *In* "Proceedings of the Fourth Annual Science Meeting, IAI CRN 03," Mendoza, Argentina October 10-16, p. 4.

Argollo, J., Soliz, C., and Villalba, R. (in preparation). Potencialidad dendrocronológica de *Polylepis tarapacana* en los Andes Centrales de Bolivia.

Boninsegna, J. A. (1988). Santiago de Chile winter rainfall since 1220 as being reconstructed by tree rings. *Quaternary of South America and Antarctic Peninsula* **6**, 67-87.

Briffa, K. R., Jones, P. D., Bartolin, T. S., Schweingruber, F. H., Karlen, W., and Shiyatov, S. G. (1996). Tree-ring variables as proxy-climate indicators: Problems with low-frequency signals. *In* "Climate variations and forcing mechanisms of the last 2000 years." (P. D. Jones, R. S. Bradley, and J. Jouzel, Eds.), pp. 9-41. NATO ASI Series, Vol. 141, Springer, Heidelberg.

Carrasco, J. F., Casassa, G., and Rivera, A. (1998). Climatología actual del Campo de Hielo Sur y posibles cambios por incremento del efecto invernadero. *Anales Instituto de la Patagonia, Serie Ciencias Naturales* **26**, 1109-1128.

Carrasco, J. F., Casassa, G., and Rivera, A. (2002). Meteorological and climatological aspects of the Southern Patagonia Icefield. *In* "The Patagonian Icefields: A unique natural laboratory for environmental and climate change studies." (G. Casassa, F. Sepúlveda, and R. Sinclair, Eds.), pp. 29-41. Series of the Centro de Estudios Científicos. Kluwer Academic/Plenum Publishers, Dortrecht.

Casassa, G., Rivera, A., Aniya, M., and Naruse, R. (2002). Current knowledge of the Southern Patagonia Icefield. *In* "The Patagonian Icefields: A unique natural laboratory for environmental and climate change studies." (G. Casassa, F. Sepúlveda, and R. Sinclair, Eds.), pp. 67-83. Series of the Centro de Estudios Científicos. Kluwer Academic/Plenum Publishers, Dortrecht.

Cook, E. R., and Peters, K. (1981). The smoothing spline: A new approach to standardizing forest interior ring-width series for dendroclimatic studies. *Tree-Ring Bulletin* **41**, 45-53.

Essenwanger, O. (1986). Elements of statistical analysis. World survey of climatology. Vol. 1B, Elsevier, Amsterdam.

González, M. E. (2002). "Fire history of *Araucaria-Nothofagus* forests in the Andean Cordillera of South-Central Chile." Ph.D. thesis, University of Colorado, Boulder.

Graham, N. E. (1994). Decadal-scale climate variability in the 1970s and 1980s: Observations and model results. *Climate Dynamics* **10**, 135-162.

La Marche, V., Holmes, R. L., Dunwiddie, P., and Drew, L. (1979). Tree-ring chronologies of the Southern Hemisphere. Vol. 2: Chile. Chronology Series V, Arizona University of Arizona.

Lara, A., and Villalba, R. (1993). A 3620-year temperture record from *Fitzroya cupressoides* tree rings in southern South America. *Science* **260**, 1104-1106.

Lara, A., Aravena, J. C., Fraver, S., and Wolodarsky-Franke, A. (1999). Fire and the dynamics of alerce *(Fitzroya cupressoides*) forests of Chile's Cordillera Pelada. *Ecosience* **6**, 100-109.

Lara, A., Villalba, R., Aravena, J. C., Wolodarsky-Franke, A., and Neira, E. (2000). Desarrollo de una red de cronologías de *Fitzroya cupressoides* (alerce) para Chile y Argentina. *In* "Dendrocronología en América Latina." (F. Roig, Ed.), pp. 217-244. Editorial Nacional de Cuyo, Mendoza.

Lara, A., Aravena, J. C., Wolodarsky-Franke, A., Villalba, R., Luckman, B., and Wilson, R. (2001). Dendroclimatology of high-elevation *Nothofagus pumilio* forests in the Central Andes of Chile. *Canadian Journal Forestry Research* **31**, 925-936.

Lara, A., Wolodarsky-Franke, A., Aravena, J. C., Cortés, M., Fraver, S., and Silla, F. (2003). Fire regimes and forest dynamics in the Lake Region of South-Central Chile. *In* "Fire an climatic change in temperate ecosystems of the Western Americas." (T. T. Veblen, T. Swetnam, and G. Montenegro, Eds.), pp. 316-336. Springer, New York.

LeQuesne, C., Aravena, J. C., Alvarez García, M. A., and Fernández Prieto, J. A. (2000). Dendrocronología de *Austrocedrus chilensis* en Chile Central. *In* "Dendrocronología en América Latina." (F. Roig, Ed.), pp. 159-175. Editorial Nacional de Cuyo, Mendoza.

Le Quesne, C., and Acuña, C. (2003). Fluctuaciones históricas del ventisquero Cipreses y su relación con el registro de anillos de *Austrocedrus chilensis* en Chile Central (Glacier (34°33'S 70°22'W). *In* "Symposium on Global Change: Towards a systemic view held at the meeting of the IGBP Scientific Steering Committee," Punta Arenas, Chile.

Luckman, B. H. (1990). Mountain areas and global change: a view from the Canadian Rockies. *Mountain Research and Development* **10**,183-185.

Luckman, B. H., and Villalba, R. (2001). Assessing the synchronicity of glacier fluctuations in the Western Cordillera of the Americas during the last millennium. *In* "Interhemispheric climate linkages." (V. Markgraf, Ed.), pp.119-140. Academic Press, San Diego, CA.

Mo, K. (2000). Relationships between low-frequency variability in the Southern Hemisphere and sea surface temperature anomalies. *Journal of Climate* **13**, 3599-3610.

Morales, M. S., Villalba, R., Grau, H. R., Villagra, P., Boninsegna, J. A., Ripalta, A., and Paolini, L. (2001). Potencialidad de *Prosopis ferox* Griseb (Leguminosae, subfamilia: Mimosoideae) para estudios dendrocronológicos en desiertos subtropicales de alta montaña. *Revista Chilena de Historia Natural* **74**, 865-872.

Miller, A. (1976). The climate of Chile. *In* "World survey of climatology. Climates of Central and South America." (W. Schwerdtfeger, Ed.), pp. 113-131. Elsevier, Amsterdam.

Naruse, R., and Aniya, M. (1992). Outline of Glacier Research Project in Patagonia, 1990. *Bulletin of Glacier Research* **10**, 31-38.

Pezoa, L. S. (2003). "Recopilación y analisis de la variación de las temperatures (período 1965-2001) y las precipitaciones (período 1931-2001) a partir de la información de estaciones meteorológicas de Chile entre los 33° y 53° de latitud sur." Tesis de grado Escuela de Ingeniería Forestal. Universidad Austral de Chile.

Prieto, M. R., and Herrera, R. (1998). Naos, clima y glaciares en el Estrecho de Magallanes durante el siglo XVI. *Anuario de Estudios Americanos*, Tomo LV-2: 413-439.

Rivera, A., Aravena, J. C., and Casassa, G. (1997). Recent fluctuations of glaciar Pío XI, Patagonia: Discussion of a glacial surge hypothesis. *Mountain Research and Development* **17**, 309-322.

Rivera, A., Casassa, G., Acuña,C., and Lange, H. (2000). Variaciones recientes de glaciares en Chile. *Investigaciones Geográficas* **34**, 25-52.

Rivera, A., Acuña, C., Casassa, G., and Bown, F. (2002). Use of remotely sensed and field data to estimate the contribution of Chilean glaciers to eustatic sea-level rise. *Annals of Glaciology* **34**, 367-372.

Roig F, Le Quesne, C., Bonisegna, J. J., Briffa, K., Lara, A., Grudd, N., Jones, P., and Villagrán, C. (2000). Climate variability 50,000 years ago in mid-latitude Chile as reconstructed from tree rings. *Nature* **410**, 567-570.

Rosenblüth, B., Casassa, G., and Fuenzalida, H. A. (1995). Recent climate changes in western Patagonia. *Bulletin of Glacier Research* **13**, 127-132.

Rosenblüth, B., Fuenzalida, H. A., and Aceituno, P. (1997). Recent temperature variations in southern South America. *International Journal of Climatology* **17**, 67-85.

Solari, M. E., Prieto, M. R., Gutiérrez, A. G., and Araya, C. (2003). Caracterización de la variabilidad a través de registros históricos del sur de Chile (41°-51° S) entre los años 1850 y 1950. *In* "Symposium on Global Change: Towards a systemic view held at the meeting of the IGBP Scientific Steering Committee," Punta Arenas, Chile.

Soliz, C., Argollo, J., Villalba, R., and Stahle, D. (2003). Climatic correlation of *Polylepis tarapacana* tree-ring chronology at Caquella Volcano in the Bolivian altiplano. *In* "Fourth Annual Scientific Meeting IAI CRN 03," Mendoza, Argentina.

Szeicz, J., Lara, A., Díaz, S., and Aravena, J. C. (2000). Dendrochronological studies of *Pilgerodendron uviferum* in southern South America. *In* "Dendrocronología en América Latina." (F. Roig, Ed.), pp. 245-270. Editorial Nacional de Cuyo, Mendoza.

Szeicz, J., Haberle, M., Simon, G., and Bennett, K. (2003). Dynamics of North Patagonian rainforests from fine-resolution pollen, charcoal and tree-ring analysis, Chonos Archipelago, Southern Chile. *Austral Ecology* **28**, 413-422.

Urrutia, R., Lara, A., Villalba, R., Pezoa, L., LeQuesne, C., Cuq, E., and Wolodarsky-Franke, A. (2003). Streamflow reconstruction from tree-ring chronologies of *Austrocedrus chilensis* and *Pilgerodendron uviferum* in the Xth Region. *In* "Fourth Annual Scientific Meeting IAI CRN 03," Mendoza.

Villalba, R. (1994). Tree-rings and glacial evidence for the Medieval Warm Epoch and the Little Ice Age in Southern South America. *Climatic Change* **30**, 1-15.

Villalba, R, Boninsegna, J. A., Veblen, T. T., Schmelter, A., and Rubulis, S. (1997). Recent trends in tree-ring records from high elevation sites in the Andes of northern Patagonia. *Climatic Change* **36**, 425-454.

Villalba, R., Lara, A., Boninsegna, J. A., Masiokas, M., Delgado, S., Aravena, J. C., Roig, F. A., Schmelter, A., Wolodarsky, A., and Ripalta, A. (2003). Large-scale temperature changes across the Southern Andes: 20th century variations in the context of the past 400 years. *Climatic change* **59**, 177-232.

Wolodarsky-Franke, A. (2002). Fluctuaciones ambientales de los últimos 1000 años a partir de anillos de crecimiento de *Fitzroya cupressoides* en el área del Volcán Apagado, X Región, Chile. Master thesis, Facultad de Ciencias, Universidad Austral de Chile.