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26. A portion of this study is supported by the Office of Health and Environmental Research, U.S. Department of Energy, as part of its Carbon Dioxide Research Program. The National Center for Atmospheric Research is sponsored by the National Science Foundation.

6 November 1992; accepted 4 March 1993

A 3620-Year Temperature Record from *Fitzroya cupressoides* Tree Rings in Southern South America

Antonio Lara* and Ricardo Villalba

A tree-ring width chronology of alerce trees (*Fitzroya cupressoides*) from southern Chile was used to produce an annually resolved 3622-year reconstruction of departures from mean summer temperatures (December to March) for southern South America. The longest interval with above-average temperatures was from 80 B.C. to A.D. 160. Long intervals with below-average temperatures were recorded from A.D. 300 to 470 and from A.D. 1490 to 1700. Neither this proxy temperature record nor instrumental data for southern South America for latitudes between 35° and 44°S provide evidence of a warming trend during the last decades of this century that could be related to anthropogenic causes. The data also indicate that alerce is the second longest living tree after the bristlecone pine (*Pinus longaeva*).

Climatic records from weather stations as well as proxy sources are scant for the Southern Hemisphere compared with those for the Northern Hemisphere (*1–4*). However, Southern Hemisphere climate records are crucial for understanding the global climatic system because climatic differences between the Northern and Southern hemispheres could provide relevant clues to the mechanisms that underlie global climatic change (*5*). Long, high-resolution paleotemperature records from the Southern Hemisphere are needed to assess the spatial patterns and extent of global warming (*2*). Here, we present an annually resolved, 3622-year summer temperature reconstruction from a tree-ring width chronology of alerce trees (*Fitzroya cupressoides*) from southern Chile.

Southern South America presents a unique opportunity for obtaining terrestrial climate proxy records in a region that is under the influence of both Antarctic and mid-latitude atmospheric circulation patterns (*6*). Tree-ring records from Argentina and Chile have proved useful for temperature and precipitation reconstruction (*7, 8*) as well as for estimating the latitudinal shifts of the Pacific high-pressure cell (*9*) and the occurrence of El Niño–Southern Oscillation events (*10*). Earlier studies of alerce produced a 1534-year ring-width chronology (*11*) and a 1120-year reconstruction of mean summer temperature variations for northern Patagonia (*7*).

We collected radial wedges from alerce stumps from a mixed conifer–broad-leaved stand that was logged from 1975 to 1976 and cores from living trees taken with increment borers in other nearby unlogged stands. These stands were located at 860- to 890-m elevation on the western slope of the Andes near Lenca in south-central Chile (41°33′S, 72°36′W; Fig. 1). The climate at the site is oceanic temperate with decreases in the summer rainfall (*12*). Lago Chapo, 18 km northeast of the study site at 240-m elevation, has a mean annual temperature of 10.3°C and receives 4140 mm of mean annual precipitation (*13*). Radial wedges and cores were surfaced and cross-dated, and ring widths were measured according to standard methods (*14*).

Of the 96 samples examined, only 43 radii (21 wedges and 22 cores) from 38 trees were successfully cross-dated. The mean length radii was 867 years (the range was 325 to 2248 years). The oldest alerce tree was dated from a wedge collected from a stump of a tree cut in 1975. Cross dating of the inner 1440 years of this tree indicated that it was 3613 years old. There were 57 locally absent rings out of a total of 37,260 rings in the cross-dated data set (0.15%). We detrended ring widths into dimensionless indices to remove the effects of changes in tree growth that resulted from aging, to homogenize the mean and variance, and to produce a standard chronology for the site (*15*). Different curve-fitting procedures for the computation of the tree-ring indices were tested (*16*). Pre-whitened residual series were combined to produce a mean chronology suitable for climate reconstruction.

Paleoclimatic interpretation of the Lenca chronology was based on the relation between alerce growth (expressed as annual tree-ring indices) and available regional temperature and precipitation records from Chile and Argentina between 39° and 44°S. We investigated these relations using response and correlation functions (*17, 18*) for various monthly and seasonal combinations of the meteorological records. There was a significant negative linear relation (slope = −2.24; SE = 0.45) between alerce tree-ring indices and previous summer (December to March) mean temperature for the period from 1910 to 1987 for a regional average of the following meteorologic stations: Colluncó, Bariloche, Esquel, Mascardi, and Sarmiento. These stations are located in Argentina east of the Andes, 140 to 485 km from the study site (Fig. 1). A similar but weaker negative relation between tree-ring indices and mean prior summer temperature (slope = −1.57; SE = 0.54) was seen for the interval from 1910 to 1987 with the use of a regional record from four stations (Valdivia, Isla Teja, Punta Galera, and Lago Chapo) located in Chile west of the Andes, 18 to 170 km from the sampling site (Fig. 1). The larger standard error associated with this regional record may be because the Chilean stations are

A. Lara, Laboratory of Tree-Ring Research, University of Arizona, Tucson, AZ 80721.
R. Villalba, Department of Geography, University of Colorado, Boulder, CO 80309.

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*Present address: Instituto de Silvicultura, Universidad Austral de Chile, Casilla 567, Valdivia, Chile.

located at low elevations near the Pacific Coast (10 to 247 m above sea level) and thus the temperature fluctuations are less than at the higher elevations (860 to 890 m) where the study site is located. A similar inverse relation between alerce tree-ring indices and prior summer temperature has been described for Río Alerce, Argentina, 80 km northeast of Lenca (*7, 19*).

The residual tree-ring chronology for Lenca as well as this chronology lagged one year backward ($T - 1$) were used to estimate departures of prior summer temperature from the mean (December to March) for the Argentinian stations east of the Andes. The observations for 1936, 1953, and 1981 were deemed to be extreme outliers by comparison with the other sample values and were not included in the regression. We performed calibration and verification tests for the periods from 1910 to 1948 and 1949 to 1987 (Table 1). Actual summer temperature departures were compared with the tree-ring estimates for the period 1910 to 1987 (Fig. 2). The variance explained by the model was about 37% after adjustment for loss of degrees of freedom as a result of the regression. Differences between the observed and predicted summer temperatures for the relatively cold period from 1935 to 1943 indicate that the model reproduces warm summers better than cold ones (Fig. 2). The transfer model was used for reconstructing the yearly departures of summer temperatures for southern South America for the period 1634 B.C. to A.D. 1987 (Fig. 3). The interval 1634 to 875 B.C. is less reliable than the rest of the reconstruction because of the small number of tree-ring series in the chronology (fewer than four; Fig. 3C).

The reconstruction of summer temperatures for southern South America (Fig. 3B) shows some periods in which summer temperatures increased or decreased for several centuries as well as some periods in which temperatures fluctuated around the long-term mean. Summer temperatures increased from 1400 to 750 B.C. and cooled from 80 B.C. to A.D. 500. The longest period that remained with temperatures above the mean was from 80 B.C. to A.D. 160. The most recent warm periods were from A.D. 1720 to 1750 and from 1800 to 1880. The longest intervals with below-average temperatures were from 770 to 570 B.C., from A.D. 300 to 470, and from A.D. 1490 to 1700. More recently, temperatures were below the long-term mean from A.D. 1750 to 1800 and from 1880 to 1930 (Fig. 3B). Our results do not provide evidence for either a warm period between A.D. 1080 and 1250, related to the medieval warm epoch reported for Europe, or two cold events (A.D. 1270 to 1380 and 1520 to 1670) contemporaneous with Little Ice Age events, which were apparent in the Río Alerce tree-ring record east of the Andes (*7*).

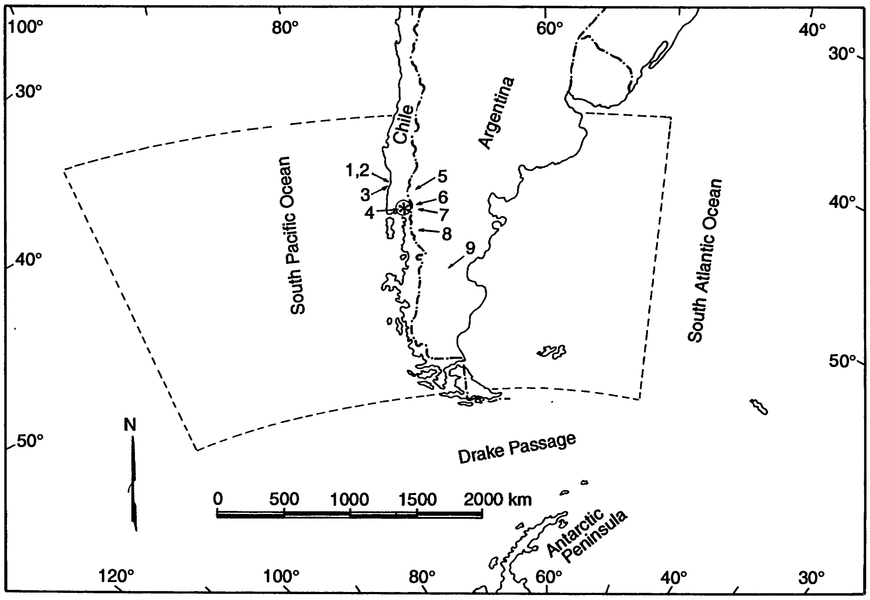

Fig. 1. Map of southern South America indicating the location of the Lenca study site (asterisk) and the meteorological stations (1, Valdivia; 2, Isla Teja; 3, Punta Galera; 4, Lago Chapo; 5, Collunc6; 6, Bariloche; 7, Mascardi; 8, Esquel; and 9, Sarmiento). The polygon (dashed lines) over the oceans indicates the area from which SST data from ship observations were averaged and used in our calculations.

Fig. 2. Observed (solid line) and predicted (dashed line) departures of summer temperatures (December to March) from 1910 to 1987. Observed departures were computed as a regional average of the following weather stations: Collunc6, Bariloche, Mascardi, Esquel, and Sarmiento. Arrows indicate the years that were deemed to be outliers and were omitted from the regression.

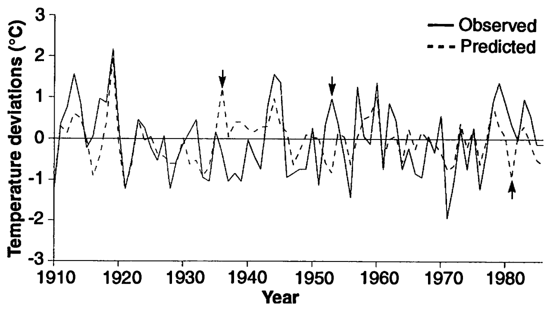

Table 1. Regression coefficients (*A* is the intercept and B_0 and B_1 are the slope for the Lenca chronology predictands in *T* and $T - 1$ positions, respectively) and selected calibration and verification statistics calculated for two subperiods and for the full time interval (A.D. 1910 to 1987). The full time interval was used to calibrate the 3622-year summer temperature departure reconstruction. SE, standard error of estimation; *r*, the Pearson correlation coefficient; RE, the reduction of error statistic; *t*, the product means test (*t* value) (*17*).

Calibration					Verification					
Period	*A*	B_0	B_1	SE	Period	Mean		*r*	RE	*t*
						Actual	Estimated			
1910–1948	5.157	−3.35	−1.82	0.69	1949–1987	−0.083	−0.012	0.59	0.33	2.86
1949–1987	5.786	−4.54	−1.33	0.66	1910–1948	−0.013	−0.100	0.64	0.37	2.55
1910–1987	5.314	−3.83	−1.53	0.67						

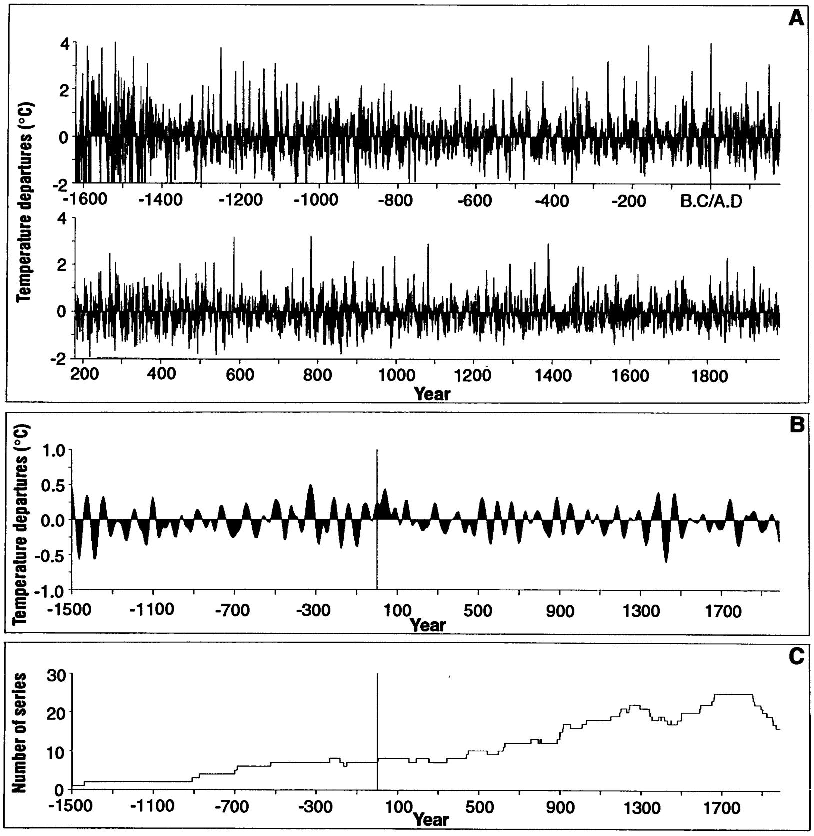

Fig. 3. Reconstruction of summer temperature departures (December to March) from the Lenca tree-ring record. (**A**) 1634 B.C. to A.D. 1987. (**B**) The reconstructed summer temperature departures (1500 B.C. to A.D. 1987) for southern South America after filtering to emphasize long-term variance (the filter is a cubic spline passing 50% of the variance in a sine function with a wavelength of 64 years). (**C**) Number of radii in the tree-ring chronology used as predictor.

The tree-ring record as well as climatic records from weather stations show that temperatures cooled from 1920 to 1935 and from 1960 to 1972 and fluctuated around the mean from 1971 to 1987 (Fig. 2). These results are consistent with the decrease in mean annual temperature from the mid-1950s to the mid-1970s in mid-latitudes (35° to 42°S) along the west coast of South America (*20*). This cooling was apparently related to cool sea-surface temperatures (SSTs) in the southern Pacific. Our results show no evidence of a warming trend since 1900, as has been reported from some meteorological stations located in southernmost South America (52° to 53°S) and other areas in the Southern Hemisphere (*2*). Our results also do not show a steady post-1965 warming described for Tasmania (40°30′S) from instrumental and tree-ring records (*3, 21*).

We investigated the regional significance of the climatic signal from the Lenca tree-ring record by analyzing the relation between tree-ring indices and prior summer (January to March) SSTs of the South Atlantic and the South Pacific oceans (*22*). For the 130-year period from 1856 to 1986, tree-ring indices from the Lenca chronology explain 22% of the variance of the mean previous summer SST of an area larger than 8 million square kilometers over the South Atlantic and the southeastern Pacific oceans (35° to 55°S and 50° to 100°W; Fig. 1). Our 3622-year temperature reconstruction is currently the longest annually resolved climate reconstruction from tree rings. In addition, this study demonstrates that alerce may live over 3600 years, which makes it the second longest living tree after bristlecone pine (*Pinus longaeva*) (*23*). Such ecologic value of alerce also enhances the need for conservation of this conifer, currently considered threatened because of illegal logging and human-set fires.

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16. Each individual series was smoothed with a 128-year spline. This detrending preserved 97% of the variance on time scales up to 50 years and 71% of the variance on time scales up to 100 years. After detrending, tree-ring series were modeled as a fourth-order autocorrelation process with the autocorrelation order determined by the minimum Akaike information criterion procedure [H. Akaike, *IEEE Trans. Automat. Cont.* **AC-19**, 716 (1974)].
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18 December 1992; accepted 23 March 1993