Quaternary Research **52,** 154–158 (1999)
Article ID qres.1999.2069, available online at http://www.idealibrary.com on IDEAL®

A 50,000-yr Pollen Record from Chile of South American Millennial-Scale Climate Instability during the Last Glaciation

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Received June 29, 1998

High-resolution (~≤100 yr sampling interval) Chilean pollen data between ~10,000 and 60,000 cal yr B.P. exhibit systematic fluctuations in Subantarctic Parkland development. These variations are dominated by a 30,000–40,000-yr cycle similar to that in the Northern Hemisphere GISP2 δ^{18}O data and other climatic records. Both Chilean and GISP2 data show oscillations in the 5000–12,000 and 1000–3000-yr period bands. The coherence is, however, generally low, and distribution of power spectra differs, with the dynamics of the pollen assemblage dominated by a combination of 12,000- and 5000-yr cycles. We suggest a preferential nonlinear response of Chilean vegetation to climatic forcing and interhemispheric differences as possible mechanisms underlying the resemblances and dissimilarities between both records. © 1999 University of Washington.

Key Words: **pollen; South America; millennial-scale paleoclimate cycles; interhemispheric comparison; Quaternary.**

Global documentation of the behavior of various climatic system components in different modes is essential to understanding present climate and predicting future climatic change. Northern Hemisphere ice-core and oceanic data record paleoclimatic variations on time scales ranging from decadal to millennial. Comparable lengthy, detailed terrestrial data are rare, particularly in the Southern Hemisphere, since few high-resolution land records extend continuously through the last glacial cycle. Previous studies of pollen from cores taken on the island of Chiloé identified the presence of interstadial/stadial oscillations in the glacial vegetation that were used to infer climate of southern Chile (Heusser *et al.,* 1999). Here we present high-resolution pollen analyses of the exceptionally well-dated 650-cm core (HE94-2B) from Taiquemó, a record that extends from the end of oxygen isotope stage (OIS) 4 through OIS 2 (Fig. 1).

The core site (42°10′25″ S, 73°35′50″, 170 m above sea level) is surrounded by remnants of temperate Valdivian Rain Forest in which *Nothofagus nitida*, *N. dombeyi*, and *Eucryphia cordifolia* dominate a diverse community of trees, lianas, and ferns (plant nomenclature follows Muñoz, 1980; Marticorena and Quezada, 1985; Marticorena and Rodríguez, 1995). Pleniglacial vegetation, for which the Magellanic Moorland of Tierra del Fuego is probably the closest modern analog (Heusser *et al.*, 1999), differed strikingly. In the record from HE94-2B (Fig. 1), Subantarctic Parkland, composed of a grass (Gramineae), shrub, and herb mosaic (*Lepidothamnus*, *Nanodea*, Chenopodiaceae, *Lebetanthus*, Caryophyllaceae, *Ribes*, *Acaena*, *Gunnera*, *Drapetes*, Umbelliferae, *Euphrasia*, Rubiaceae, *Plantago*, *Valeriana*, *Huperzia*, *Ephedra*, and Compositae), alternated systematically with relatively open Subantarctic Evergreen Forest (*Podocarpus*, *Pilgerodendron* type, *Pseudopanax*, Myrtaceae, *Embothrium*, *Lomatia*, *Maytenus*, *Drimys*, and *Weinmannia*) and heath (*Empetrum*-Ericaceae). Southern beech (*Nothofagus* cf *betuloides*) was present throughout.

The overall temporal pattern of development of subantarctic forest types (excluding southern beech) (Table 1, Fig. 1) resembles orbital-scale climatic variations captured in Northern and Southern Hemisphere δ^{18}O and δD records (Bender *et al.*, 1994). Major intervals of forest expansion coincide within the

0033-5894/99 $30.00

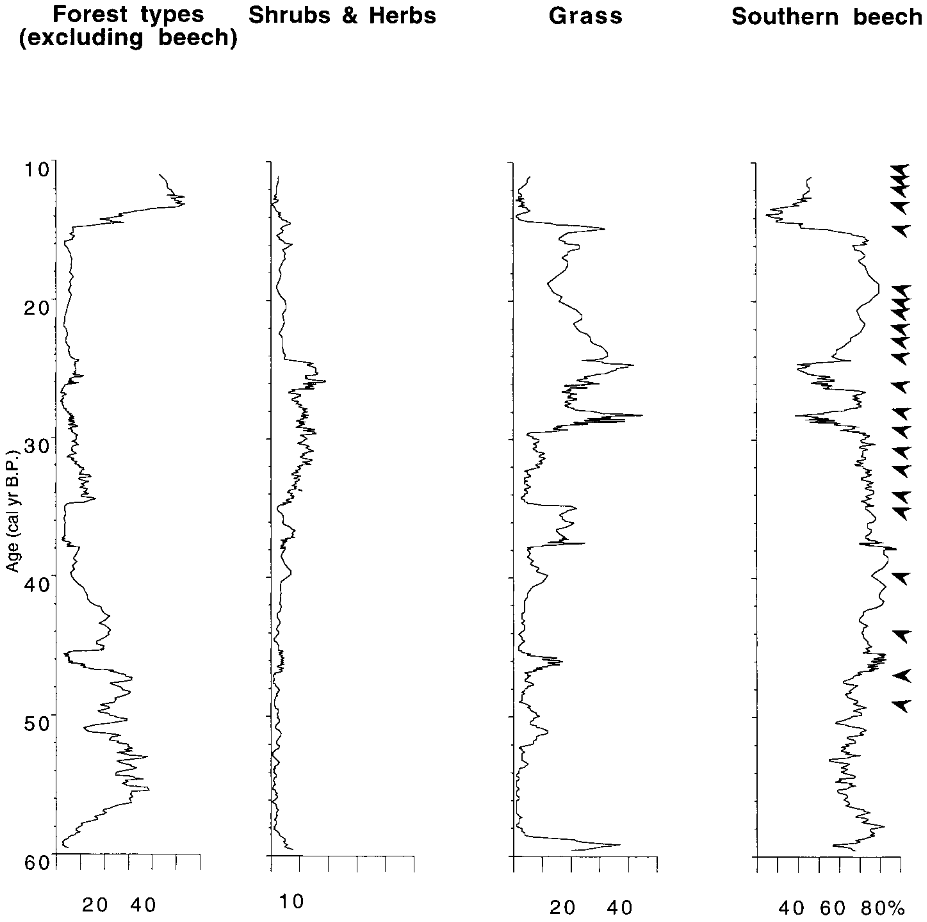


FIG. 1. Time series of pollen assemblages from core HE 94-2B taken in a mire near Fundo Taiquemó, Chile. Percentages which account for 98% of the pollen data (shown here smoothed with a 3-point average to emphasize the broad structure), are based on counts of >300 pollen grains/sample from 570 samples taken at 1 cm intervals (C.J.H.). The age model derives from 30^{14}C AMS dates from the 22 levels shown by arrows (Table 1, Fig. 1) adjusted using Laj *et al.* (1996) and placement of the OIS3/4 boundary (59,000 cal yr B.P.) at 618 cm core depth (Martinson *et al.,* 1987).

limit of radiocarbon age precision with European interstadial (IS) forest expansions (IS 5–7,11,14, and 15–17, the Danekemp, Hengelo, Glinde, and Oerel, respectively). These, in turn, correspond to warming events identified in ice and marine cores (Bender *et al.,* 1994).

Grass assemblages (grass accompanied by subantarctic herb and shrub taxa, such as *Lepidothamnus fonkii, Astelia pumila, Drapetes muscosus, Donatia fascicularis, Euphrasia,* and *Huperzia fuegiana*) show a steady sequence of brief peaks, which increase in amplitude and have maxima at ~28,000, ~24,000, ~20,000, ~16,000, and 14,000 cal yr B.P. These events are considered coeval with maxima of piedmont glacier lobes in the Chilean Andes and the Southern New Zealand Alps (Denton *et al.,* 1999), and with stadial events in the North Pacific (Behl and Kennett, 1996) and North Atlantic (Bond *et al.,* 1997). Prior to ~30,000 cal yr B.P., there also appears to be correspondence between grassland expansion in southern Chile and Northern Hemisphere paleoclimate proxies, for example, δ^{18}O in Greenland ice and North Atlantic and North Pacific ice-rafted detritus (Bond *et al.,* 1997; Kotilainen and Shackleton, 1995).

Climatic interpretation of the southern Chile pollen record is based on comparing fossil pollen spectra with modern pollen spectra, vegetation, and climate (Heusser *et al.,* 1999). Stadial intervals with high amounts of grass reflect open parkland with estimated summer temperatures of ~6°C (~8°C below present). Interstadials characterized by increased representation of thermophilous components in the Subantarctic Evergreen Forest imply summer temperatures of ~12°C. Effective precipitation, which averages 4000 mm in the wet, oceanic climate of Chiloé, probably was not a critical factor in subantarctic vegetation development (Heusser *et al.,* 1999). Rapid oscillations of the paleoclimate indicators (Fig. 1) are superposed on a general cooling trend, which culminates at the last glacial maximum (OIS 2). Temporal changes in southern Chilean climate inferred from the HE94-2B pollen data resemble millennial-scale oscillations found in various Northern Hemisphere climate proxies between ~10,000 and 60,000 cal yr

TABLE 1
Chronostratigraphic Data for Core HE94-2B

Depth (cm)	Age (^{14}C yr B.P.)	Laj-adjusted age[a]	Lab. no.
90	10,355 ± 75	11,655	AA-17974
95	11,050 ± 75	12,450	AA-17975
105	11,360 ± 80	12,760	AA-17976
115	12,300 ± 90	13,750	AA-17977
125	13,040 ± 98	14,540	AA-14751
145	15,200 ± 100	17,100	AA-17980
160	19,020 ± 130	21,920	AA-17982
170	20,160 ± 200	24,160	AA-17984
180	21,430 ± 200	24,630	AA-17985
190	21,960 ± 170	25,160	AA-17986
200	22,601 ± 194	25,901	AA-14754
215	22,774 ± 202	26,074	AA-17989
230	23,293 ± 200	26,593	AA-17990
260	24,985 ± 232	28,195	AA-17991
300	26,019 ± 317	29,419	AA-14758
325	28,185 ± 330	31,385	AA-14759
350	29,718 ± 495	32,767	AA-14760
375	31,674 ± 565	34,474	AA-14761
385	32,105 ± 549	34,805	AA-17992
400	34,375 ± 632	37,075	AA-14762
435	35,441 ± 714	37,941	AA-17993
450	40,011 ± 1505	41,911	AA-14764
470	44,520 ± 2102	45,200	AA-17994
525	47,110 ± 2893	47,010	AA-14767

[a] Laj *et al.* (1996)

B.P. (Grimm *et al.*, 1993; Bond *et al.*, 1997; Lund and Mix, 1998).

Recognizing the uncertainties in temporal correlations constrained by age models in which dating precision is not always consistent (Bender *et al.*, 1994) and possible differences in the insolation forcing in different hemispheres, we investigated relationships between the grass component of Chilean Subantarctic Parkland and Northern Hemisphere atmospheric records (δ^{18}O of a Greenland ice core, Grootes *et al.*, 1993). The data were first explored in the time domain for the period covered by the whole record from Chile (Fig. 2a) and then for the part between 25,200 and 56,200 cal yr B.P. (Fig. 2b). In this study, no tuning was done to the age model for the grass record. Spectral analysis (Blackman-Tukey, ARAND by P.J. Howell, Brown University) was used to study the cyclicity and coherence of the records (Figs. 2c and 2d corresponding to Figs. 2a and 2b, respectively).

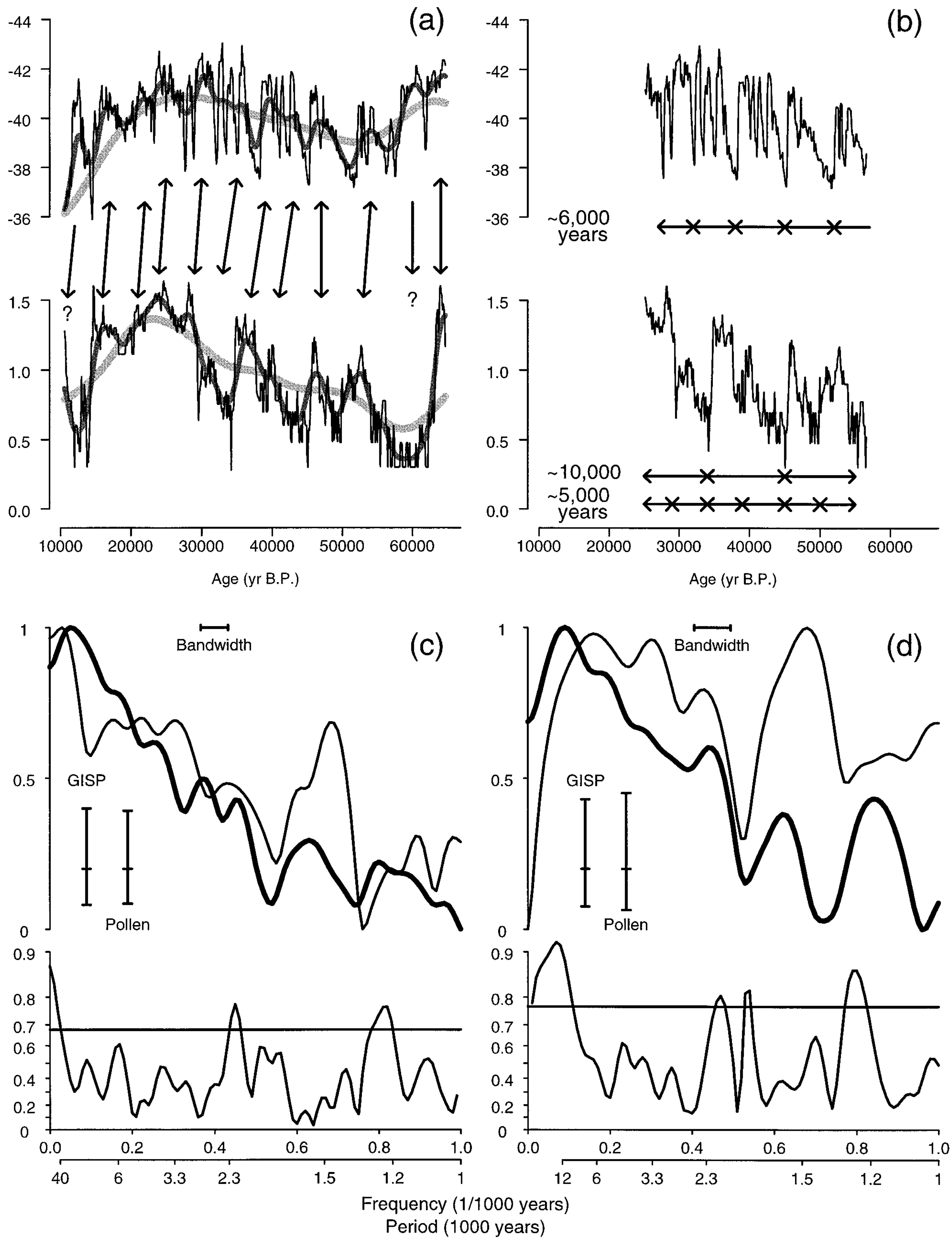
The coherence between Chilean grass and Northern Hemisphere δ^{18}O ice records (Figs. 2c and 2d) was found to be generally lower than that between marine records. For the whole time series, the concentration of coherence and spectral power at low frequencies (Fig. 2c) suggests a common trend with a temporal span comparable to the length of the time series (this effect may be interpreted as a nonstationarity of the series). Such a long-term trend is clearly visible in Figure 2a (thick gray line), as both the Chilean and GISP2 records are dominated by the characteristic saw-tooth pattern with a duration of ~30,000–40,000 yr.

In the Chilean record, the long-term variations mask the behavior of the higher frequencies in the spectral analysis (Fig. 2c). To increase the resolution of analyses in the high-frequency domain, we also considered both records between 25,200 and 56,200 cal yr B.P. (Figs. 2b and 2d). When these records are additionally linearly detrended (not shown), they no longer appear nonstationary and show more consistent cyclicity (Fig. 2d). The pollen record is dominated by cycles with a period of ~5000–6000 yr modulated at 10,000–12,000 yr (see Fig. 2d, and spacing of the minima in Fig. 2b). The GISP2 sequence oscillates with a similar ~6000-yr period, that is clearly visible in Figure 2b. Although the 10,000–12,000-yr signal is not readily apparent in the spectral analysis of the ice-core data, more sensitive methods (maximum entropy) show the presence of such cycles by splitting the broad peak in Figure 2d. This explains a relatively high coherence with the grass signal at the corresponding frequency.

In addition to a long-term trend, the GISP2 record is dominated by high-amplitude and high-frequency oscillations (1000–3000-yr periods, Figs. 2c and 2d). Such periods are present in the pollen record but with a much smaller amplitude. This descrepancy could be a result of nonlinearity in the response of the vegetation to climatic forcing, with a preferential selection of lower frequencies.

Little coherence occurs at periods around 6000 yr and 1500

FIG. 2. Comparison of the Northern Hemisphere (GISP2) δ^{18}O ice core record and the grass record from Chile in the temporal and frequency domains. (a) The δ^{18}O ice core record (top graph) compared with the Chilean grass record transformed by $\log(1 + x)$ (bottom graph) for the interval between ~10,000 and 60,000 cal yr B.P. Solid lines show the records interpolated to the common equal interval of 100 yr by Gaussian kernel smoothing (100-yr bandwidth). A common long-term trend (thick gray line, 30,000–40,000 yr periodicity) and the cyclicity at 5000–6000 yr and 10,000–12,000 yr (thin gray line) have been made visible by independent smoothing of both records with a Gaussian kernel, with bandwidths of 10,000 yr and 2,000 yr, respectively. Arrows mark potential similarities, which might be used for "wiggle matching" techniques. The sedimentation rate, dating, and periodicity implications of such adjustments would need careful evaluation. (b) The middle parts of both records, between 25,200 and 56,200 cal yr B.P. show apparent cycles with periods of ~6000 yr (GISP2) and ~5000 yr and ~10,000 yr (Chilean pollen data). (c) Normalized power spectra of GISP2 δ^{18}O (thin line) and Chilean pollen data (thick line) between 10,000 and 60,000 yr, with 200 lags; and (d) spectra of GISP2 δ^{18}O (thin line) and Chilean pollen data (thick line) between 25,200 and 56,200 cal yr B.P. All records were linearly detrended prior to spectral analysis. Coherence (plotted here on an inverse hyperbolical tangent scale) is shown in the bottom part of (c) and (d). The horizontal line in the coherence plot corresponds to the 80% confidence limit; the error bars correspond to confidence intervals of the spectral power (additive on the log-plot). These results were also tested by comparison with other methods, notably Burg's (maximum entropy) method (not shown here), and the results were found to be consistent.


(a)
-44
-42
-40
-38
-36
1.5
1.0
0.5
0.0
?
?
10000
20000
30000
40000
50000
60000
Age (yr B.P.)
(b)
~6,000 years
~10,000
~5,000 years
Age (yr B.P.)
(c)
Bandwidth
GISP
Pollen
1
0.5
0
0.9
0.8
0.7
0.6
0.4
0.2
0.0
0.2
0.4
0.6
0.8
1.0
40
6
3.3
2.3
1.5
1.2
1
(d)
Bandwidth
GISP
Pollen
12
6
3.3
2.3
1.5
1.2
1
Frequency (1/1000 years)
Period (1000 years)

yr, even though both records show a substantial spectral power concentrated at the corresponding frequencies. The apparent correlation of cycles at 5000–6000 yr in both records is also seen in Figures 2a and 2b (see arrows there). At present we have no satisfactory explanation of the lack of coherence of such cycles, but differences in the amplitude modulation and/or phase shifts within the sequence can be suggested as possible mechanisms.

In this paper we compare two high-resolution records, the Chilean grass record and the Northern Hemisphere ice-core data. While there is ample evidence for a high degree of similarity between the data, evidence also exists for substantial dissimilarities. The mechanisms for the differences, including the nonlinear response of the vegetation to the climatic forcing and the interhemispheric synchronizations and desynchronizations, deserve further investigation. In particular, the comparison with other climatic and vegetation records from both hemispheres (including Vostok and Byrd Station data; Johnsen *et al.*, 1987) needs to be combined with testing different interpretations of the age model for the Chilean record. Subsequently such tests may help to determine the implications of the apparent phase and amplitude changes during OIS 3.

ACKNOWLEDGMENTS

We thank M. Chapman, J. Gavin, T. Lowell, R. Lotti, A. Mix, N. J. Shackleton, T. van Andel, and the Godwin Institute of Quaternary Research, University of Cambridge. This project was funded in part by grants from NSF, NOAA, and by a King's College Senior Research Fellowship (awarded to A.K.). Cores were curated by Lamont-Doherty Earth Observatory Deep-Sea Sample Repository, which is supported by NSF and ONR.

REFERENCES

Behl, R., and Kennett, J. (1996). Brief interstadial events in the Santa Barbara basin, NE Pacific, during the past 60^{14}C yr B.P. *Nature* **379,** 243–245.

Bender, M., Sowers, T., Dickson, M.-L., Orchardo, J., Grootes, P., Mayewski, P., and Meese, D. (1994). Climate correlations between Greenland and Antarctica during the past 100,000 years. *Nature* **372,** 663–666.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., de Menocal, P., Priore, P., Cullen, H., Hajdas, I., and Bonani, G. (1997). A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates. *Science* **278,** 1257–1266.

Denton, G. H., Heusser, C. J., Lowell, T. V., Moreno, P. I., Andersen, B. G., Heusser, L. E., Schlüchter, C., and Marchant, D. R. (1999). Interhemispheric linkages of paleoclimate during the last glaciation. *Geografiska Annaler* **81A,** 107–153.

Grimm, E. C., Jacobson, G. L., Watts, W. A., Hansen, B. C. S., and Maasch, K. A. (1993). A 50,000-year record of climate oscillations from Florida and its temporal correlation with Heinrich events. *Science* **261,** 198–200.

Grootes, P. M., Stuiver, M., White, J. W. C., Johnsen, S., and Jouzel, J. (1993). Comparison of oxygen-isotope records from the GISP2 and GRIP Greenland ice cores. *Nature* **366,** 552–554.

Heusser, C. J., Heusser, L. E., and Lowell, T. V. (1999). Paleoecology of the Southern Chilean Lake District-Isla Grande de Chiloé during middle-late Llanquihue glaciation and deglaciation. *Geografiska Annaler* **81A,** 231–284.

Johnsen, S. J., Clausen, H. B., Dansgaard, W., Fuhrer, K., Gundestrup, N., Hammer, C. U., Iversen, P., Jouzel, J., Lorius, C., Petit, J.-R., Genthon, C., Barkov, N. I., Kotyakov, V. M., and Petrov, V. M. (1987). Vostok ice core: a continuous isotope temperature record over the last climatic cycle (160,000 years). *Nature* **329,** 403–407.

Kotilainen, A., and Shackleton, N. J. (1995). Rapid climate variability in the North Pacific Ocean during the past 95,000 years. *Nature* **377,** 323–326.

Laj, C., Mazaud, A., and Duplessy, J.-C. (1996). Geomagnetic intensity and ^{14}C abundance in the atmosphere and ocean during the past 50 kyr. *Geophysical Research Letters* **23,** 2045–2048.

Lund, D., and Mix, A. C. (1998). Millennial-scale deep water oscillations: Reflections of the North Atlantic in the deep Pacific from 10 to 60 ka. *Paleoceanography* **13,** 10–19.

Marticorena, C., and Quezada, M. (1985). Catálago de la flora vascular de Chile. *Gayana* **42,** 1–157.

Marticorena, C., and Rodríguez, R. (1995). "Flora de Chile. Vol. 1. Pteridophyta-Gymnospermae." Universidad de Concepción, Concepción, Chile.

Martinson, D., Pisias, N., Hays, J., Imbrie, J., Moore, T. C., Jr., and Shackleton, N. (1987). Age dating and the orbital theory of the Ice Ages: Development of a high-resolution 0 to 300,000-year chronostratigraphy. *Quaternary Research* **27,** 1–29.

Muñoz, M. (1980). "Flora del Parque Nacional Puyehue." Editorial Universitaria, Santiago, Chile.