Chilean and Southeast Pacific paleoclimate variations during the last glacial cycle: directly correlated pollen and $\delta^{18}$O records from ODP Site 1234

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Abstract

Joint pollen and oxygen isotope data from Ocean Drilling Program Site 1234 in the southeast Pacific provide the first, continuous record of temperate South American vegetation and climate from the last 140 ka. Located at $\sim$36°S, $\sim$65 km offshore of Concepcion, Chile, Site 1234 monitors the climatic transition zone between northern semi-arid, summer dry-winter wet climate and southern year-round, cool temperate climate. Dominance of onshore winds suggests that pollen preserved here reflects transport to the ocean via rivers that drain the region and integrate conditions from the coastal mountains to the Andean foothills. Down-hole changes in diagnostic pollen assemblages from xeric lowland deciduous forest (characterized by grasses, herbs, ferns, and trees such as deciduous beech, *Nothofagus obliqua*), mesic Valdivian Evergreen Forest (including conifers such as the endangered *Prumnopitys andina*), and Subantarctic Evergreen Rainforest (comprised primarily of southern beech, *N. dombeyi*) reveal large rapid shifts that likely reflect latitudinal movements in atmospheric circulation and storm tracks associated with the southern westerly winds. During glacial intervals (MIS 2-4, and 6), rainforests and parkland dominated by *Nothofagus* moved northward into the region. At the MIS 6/5e transition, coeval with the rapid shift to lower isotopic values, rainforest vegetation was rapidly replaced by xeric plant communities associated with Mediterranean-type climate. An increased prominence of halophytic vegetation suggests that MIS 5e was more arid and possibly warmer than MIS 1. Although rainforest pollen rises again at the end of MIS 5e, lowland deciduous forest pollen persists through MIS 5d and 5c, into MIS 5b. Substantial millennial-scale variations occur in both interglacial and glacial regimes, attesting to the sensitivity of the southern westerly belt to climate change. Comparison of the cool, mesic *N. dombeyi* rainforest assemblage from Site 1234 with $\delta^{18}$O in the Byrd Ice core shows that on time scales longer than $\sim$10 ka, cool-moist conditions in central Chile were coherent with and occurred in phase with Antarctic cooling. This is also likely at millennial scales, although rainforest pollen lags Antarctic cooling with exponential response times of about 1000 years, which plausibly reflects the ecological response time to regional climate change.

1. Introduction

Uncertainty about the evolution of natural variations in present (and future) interglacial climate and of terrestrial environments stems from the fact that, despite the extensive information derived from lengthy ice and marine cores, terrestrial climatic records of previous interglacial episodes are rare and are difficult to set into a chronostatigraphic framework. Shackleton (1969) introduced the relevance of marine oxygen isotope stratigraphy to Quaternary stratigraphy and suggested that Marine Isotope Stage (MIS) 5e was the marine equivalent of the “most temperate part of the Eemian” interglacial stage of northwest Europe. Ten years later, using directly correlated oxygen isotope and pollen records from a core taken in the northeast Pacific Ocean, Heusser and Shackleton (1979) confirmed the global interglacial status of MIS 5e. Subsequently, joint oxygen-isotope-pollen analyses of marine cores have provided chronostratigraphically controlled evidence of past interglacial climates in North America, Japan, Africa, Australasia, and western Europe.
(e.g., Dupont et al., 2000; Friddell et al., 2002; Heusser and Morley, 1997; Hope et al., 2004; Lyle et al., 2001; Sanchez Goñi et al., 1999). Here we present the first such evidence from South America.

1.1. Climate

Primary regional climatic controls of southern Chile are the low Coastal Mountains and lofty, ice-capped Andes that border the Central Valley, and the waters offshore that include the northward-flowing Peru-Chile Current and the southward-flowing Peru–Chile Counter Current (Fig. 1) (Strub et al., 1998) Due to the low land/ocean ratio (average breadth is $\leq 150$ km) and moderating oceanic influence, climate is highly equable. Between $34^\circ$ S and $41^\circ$ S, annual mean temperatures decrease poleward from $\sim 15$ to $\sim 11$ $^\circ$C on the Chilean coast, and from $\sim 14$ to $\sim 6$ $^\circ$C offshore (Miller, 1976). Between $30^\circ$ S and $40^\circ$ S, average annual precipitation increases from $< 150$ to $> 3000$ mm. This remarkable contrast in rainfall—the change from the northern mild, semi-arid, summer dry-winter wet climate to southern, year-round, rainfall, reflects control of dominant storm tracks by the subpolar oceanic front in the South Pacific. This frontal zone also coincides with the transition between dominant coastal upwelling to the north, which promotes coastal fog that influences coastal vegetation, and coastal downwelling to the south. Associated seasonal shifts in the latitude of the southern westerlies and in the Peru–Chile Current and Counter–Current transition reflect interactions between the quasi-permanent South Pacific Tropical High and Polar Low pressure systems.

1.2. Vegetation

Net precipitation is the primary factor in the distribution of southern Chilean vegetation types; latitudinal and altitudinal temperature variation and disturbance factors such as volcanism and earthquakes are secondary (Veblen et al., 1981). The ecotone between subtropical sclerophyllous woodland and rainforest is broad and uneven, with many rainforest elements extending far north of the climatic boundary at $\sim 36^\circ$ S. Natural forested regions can be divided into two major groups: northern lowland deciduous forest ($\sim 36^\circ$ S to $\sim 40^\circ$ S) and southern evergreen and deciduous forests (Schmithüsen, 1956). Deciduous beech forest occurs on the lower slopes of the cordilleras and extends to $\sim 41^\circ$ S in the Central Valley where it merges

![Fig. 1. (left) Site 1234 is located about 65 km off the Chilean coast. Surface circulation is marked by the northward flowing Peru-Chile Current (PCC), Chilean Fjord Water (CFW), and the Antarctic Circumpolar Current (ACC). Sea surface temperatures are in $^\circ$C (Ocean Climate Laboratory, 1999). (right) Present distribution of vegetation in southern Chile. Evergreen rain forest is shown in green, deciduous beech forest in pink, subtropical broad sclerophyllous woodland and plantations of $P.$ radiata in tan, and high-elevation Andean beech forest and tundra in red. Non-forested areas are yellow. Vegetation of Tagua Tagua is semiarid sclerophyllous woodland. That of Taiquemo is mesic evergreen forest (Heusser, 2003).]
with evergreen rain forest (Valdivian Evergreen Forest) (Fig. 1; Heusser, 2003). North Patagonian Evergreen Forest extends from ~43°S to ≥47°30’S. Further south, Subantarctic Evergreen Forest is dominated by cold-tolerant Nothofagus species (Heusser, 2003). Altitudinal stratification of vegetation in the Coastal Mountains and western slopes of the Andes is a condensed replica of the latitudinally controlled vegetation and climatic zones of southern Chile (Paez et al., 1997).

In the Central Valley, forest comprised mainly of deciduous beech (N. obliqua), often accompanied by the conifer Podocarpus saligna, occurs on well-drained volcanic and glacial soils (Lusk, 1996). Coastal natural vegetation is a mosaic of xeric N. obliqua forest, sclerophyllous woodland on sandy soils, and mesic N. dombeyi and myrtaceous forests in zones of high humidity (Veblen et al., 1983). Littoral deposits include sclerophyllous and myrtaceous forests, wetlands (marshes and swamps with Myrtaceae and Cyperaceae), and halophytic shrubs and herbs. The highly diverse arboreal component of the low-elevation to mid-elevation Valdivian rainforest includes the shade-intolerant southern beech (N. dombeyi) opportunistic genera of Myrtaceae (Luma and Myrcygenia), epiphytes (Misodendrum), and ferns (Filiicinaceae). Between ~36°S and 38°S, small, scattered populations of the rare, endangered conifer Prumnopitys andina are found in association with Nothofagus between ~200 and ~1270 m on the west slopes of the Andes (Rodriguez, 2004).

At higher elevations on both cordilleras, North Patagonian rainforest includes N. nitida (N. dombeyi type pollen) accompanied by the cold-resistant conifer P. nubigena, Lomatia ferruginea and the myrtaceous Anomyrus (Heusser, 2003).

2. Materials and methods

The primary core site (site 1234, 36°13.15′S, 73°40.90′2′′W, 1015 m water depth) was purposely located ~65 km off the Chilean coast in order to obtain directly correlatable terrestrial and marine records (Mix et al., 2003). Downslope transport of turbidity flows is channeled into an incised canyon system, leaving a complete and undisturbed hemipelagic record containing abundant, well-preserved biogenic components. Sediment accumulation is rapid (on average 140 cm/ka), providing a very high-resolution record. Because of the year-round onshore winds, aeolian transport of pollen and other fine-grained terrigenous components to the continental margin is minimal and fluvial transport is maximal (Campos et al., 1998; Heusser, 1978; Lamy et al., 2001). Regional river transport is dominated by the Rio Bio Bio, which originates as Andean streams and flows through the Central Valley and Coastal Mountains, draining an area of ~24,000 km². Given this fluvial input, pollen preserved at Site 1234 likely integrates conditions within the drainage area and is broadly representative of conditions in transition zone between dry Mediterranean-type climates with deciduous forests to the north, and the wet climates and temperate rainforests to the south.

As is common practice for ODP sites, a complete and continuous record is developed from a composite section comprised of three separate boreholes, and depths are referred to as meters composite depth (mcd). Details of coring procedures and development of the composite section are documented elsewhere (Mix et al., 2003). Discrete samples from the upper 100 m of the composite core were subdivided for analysis of pollen and oxygen isotopes of benthic foraminifera. In the younger parts of the section, selected samples were used for radiocarbon dating of benthic foraminifera.

Pollen was extracted from 525 samples by sieving with 7 μm screens prior to and following chemical (HCl, HF, acetolysis) treatment (Heusser and Stock, 1984). In all samples, pollen was well preserved. Pollen identification, based on comparison with our collection of South American reference slides and photos (Heusser, 1971), was conservative. Morphologically-similar pollen taxa were grouped as follows: N. dombeyi, N. nitida, N. betuloides, N. antarctica, N. pumilio, N. alessandrii, and N. leonii as N. dombeyi type that is referred to in the text as N. dombeyi; N. obliqua, N. alpina, and N. glauca as N. obliqua type that is referred to in the text as N. obliqua; Myrtaceous genera found in our region (Anomyrus, Ugni, Myrcygenia, and Blerpharocalyx) as Myrtaceae; and P. saligna and P. nubigena as Podocarpaceae. Pollen percentages are based on average counts of ≥175 grains that represent ~40 pollen types. Percentages of spores are based on the sum of pollen and spores. Pollen concentration (pollen grains per gram dry weight sediment) is based on the ratio of indigenous pollen grains to exotic spores that were added in the initial processing.

Pollen data reported here are compared with data reported elsewhere from ODP Site 1233 (Pisias et al., 2006), and from Laguna de Tagua Tagua (Heusser 1990). Stable isotopes reported here were analyzed at the College of Oceanic and Atmospheric Science, Oregon State University (AM—414 samples from 0 to 59 mcd, separate analyses if Uvigerina pygmae, and Cibicidoides sp., on average 5 shells per analysis) and at Woods Hole Oceanographic Institution (JM—197 samples from 50.5 to 94.1 mcd; in most cases single shells of Cibicidoides sp). To combine the results from the two species, 0.64 was added to all analyses based on Cibicidoides, and replicate analyses were averaged. Details of these results will be reported elsewhere. At both institutions, isotopic analyses were performed on Finnigan/MAT-252 mass spectrometers equipped with a “Kiel” automated carbonate extraction system (version 1 at WHOI, version 3 at OSU). At both institutions, samples are reacted with 100% phosphoric acid at 70 °C, and cryotrapped prior in expansion in a dual viscous inlet.

External precision of replicate δ18O analyses at the two institutions is essentially identical (+0.06% at OSU, +0.07% at WHOI), and both calibrate to the widely used
Vienna Pee Dee Belemnite (VPDB) standard via several certified carbonate standards provided by the US National Institute of Standards and Technology (NIST), as well as local standards. At both institutions, the primary standard is NIST-8544 (also known as NBS-19 limestone) with certified values of $-2.20\%$ and $+1.95\%$ for $\delta^{18}O$ and $\delta^{13}C$, respectively (no precision estimate; NIST, 1992b). Given this calibration, at OSU the isotopic values and precision obtained for NIST-8543 (also known as NBS-18 carbonatite) were $-23.02\pm 0.11\%$ for $\delta^{18}O$, and $-5.04\pm 0.04\%$ for $\delta^{13}C$ ($n = 23$), which compares with certified values of $-23.05\pm 0.19\%$ and $-5.04\pm 0.06\%$ for $\delta^{18}O$ and $\delta^{13}C$, respectively (NIST, 1992a). As an additional check on isotopic calibration, OSU continues to run the traditional standard NBS-20 (Solenhofen Limestone). For this unofficial standard we measured isotopic values and precision of $-4.13\pm 0.06\%$ for $\delta^{18}O$ and $-1.05\pm 0.02\%$ for $\delta^{13}C$ ($n = 19$), which compares well with the traditional values of $-4.14\%$ and $-1.06\%$ that are commonly used in the literature.

3. Stratigraphy and chronology

The age model for Ste 1234 was developed based on AMS radiocarbon dates in from 0 to 20 ka (calendar corrected using CALIB 5.1), from 20 to 75 ka based on correlation of the benthic $\delta^{18}O$ to deep Atlantic core MD95204 (Shackleton et al., 2000), and from 75 to 150 ka by correlation to the Vostok ice core chronology of Shackleton et al. (2004). Within MIS 3, this correlation is confirmed by the presence of the Laschamp paleomagnetic excursion (41.5 ka) at a depth of $\approx 24$ mcd (Lund et al., in press; Mix et al., 2003).

Data from Site 1234 are compared with similar data from ODP Site 1233, in which the age model is constrained by 25 calendar corrected $^{14}C$-AMS dates (Lamy et al., 2004) over the upper 75 mcd of ODP Site 1233. At site 1233, the AMS $^{14}C$ ages place the Laschamp magnetic event at 41.5 ka, an age that agrees with previous estimates.

The age model for Tagua Tagua is based on linear interpolation of 12 published radiocarbon dates (Heusser, 1990) that were corrected using Calpal 2004 (http://www/calpal.de).

3. Results and discussion

3.1. Dynamic changes in vegetation

Except for two short intervals between 0–5 and 83–87 mcd, *N. dombeyi* dominates the entire pollen record from ODP Site 1234 (Fig. 2). Percentages of *N. dombeyi* drop abruptly from basal (>87 mcd) values of $\approx 55–20\%$ (83–87 mcd), are followed by a gradual increase and return to high values between $\approx 48$ and 42 mcd. After decreasing to $\approx 30\%$ at $\approx 32$ mcd (lower MIS 3), percentages again increase and oscillate between $\approx 40$ and $>50\%$ until a precipitous drop to $\approx 20\%$ at $\approx 5$ mcd. The inverse pattern is seen in *N. obliqua*, *Podocarpus* (cf. *P. saligna*), Filicinae,
and other taxa that peak during the two deepest *N. dombeyi* minima. Periodic, high-amplitude variations in *P. andina* occur throughout. Rising to an initial high of ~14% at ~84 mcd, percentages decrease to ~≤2%, amounts comparable to those in the upper 1–2 m. Three asymmetric peaks, at ~71, ~64, and ~52 mcd, which reach values of 22%, 21%, and 38%, respectively, are followed by lesser maxima at ~50, ~46, and ~42 mcd. After a gradual increase to 30% at ~32 mcd, maxima of *P. andina* decline to ~18% at ~11 mcd and then increase to ~25% at ~4 mcd.

When viewed in the time domain, the pattern match between the ODP Site 1234 pollen spectra and benthic δ¹⁸O signal is obvious (Fig. 2). Most striking is the negative correlation between *N. dombeyi* and δ¹⁸O. Dropping from maximum values in MIS 6 to minimum values in MIS 5e in precisely the same samples as the isotopic shift at Termination II, the two records continue in tandem. After the lesser pollen minima of MIS 5c and 5a, *N. dombeyi* increases in MIS 4 to values equaling the full glacial values of MIS 6—values that are again reached and maintained from the latter part of MIS 3 through MIS 2. At Termination I, as at Termination II, the *N. dombeyi* and isotope shifts are essentially synchronous. Patterns of other major pollen groups (*N. obliqua, Gramineae, and Filicinae*) also generally track variations in δ¹⁸O.

During the two interglacials, however, both the amplitude and the sequence of pollen types differ. In MIS 5e, the rise of *N. obliqua*, *Lomatia*, and *Myrtaceae* is followed by a rapid increase in *Podocarpus* at the MIS 5e/MIS 5d transition. In MIS 1, the expansion of *N. obliqua*, to values well above those of MIS 5e, follows the peaks of *P. andina*, and ferns (Filicinae) that mark the deglacial transition. Percentages of *Lomatia* and *Podocarpus* remain at or close to glacial levels, while herb percentages (Gramineae, Compositae, and Chenopodiaceae) are well above those of MIS 5e. *Podocarpus* seems to be in antiphase with δ¹⁸O in MIS 5e; during MIS 1 it is more in phase.

To clarify the complex variations in the amplitude and duration of oscillations in the marine pollen data, we synthesized tabulations of 15 significant pollen types from ODP Sites 1234 and 1233 using Q-mode factor analysis (Table 1)(Fig. 3). Dominated by *N. dombeyi* and its associated mistletoe-like parasite *Misodendrum*, the *N. dombeyi* factor is the signature of southern evergreen rainforests (Heusser, 2003). The second factor, in which the endangered conifer *P. andina* is most important, reflects Andean pre-cordilleran rainforest. The Herb (Gramineae and Compositae) and Filicinae factors capture the role of open vegetation in xeric (shrublands, sclerophyllous woodlands, and lowland deciduous forests) and mesic (rainforests) ecosystems, respectively.

Variations in the downcore loadings of pollen assemblages from ODP Site 1234 reflect systematic changes in the regional vegetation in the subtropical-temperate ecotone of southern Chile. Clearly, the distribution of cool, mesic rainforests and warm, xeric vegetation in the climatic transition zone of Chile changed repeatedly and rapidly over the last 140 ka, and seldom resembled vegetation of the present interglacial. Since the end of the penultimate glacial, evergreen rainforest of variable composition has dominated the landscape, with major exceptions during MIS 5 and MIS 1 (Figs. 2 and 3). Beginning ~140 ka, except for a brief reduction at ~137 ka that corresponds with a δ¹⁸O low, *N. dombeyi* rainforest dominance continued until ~128 ka when it was rapidly replaced by open shrublands, woodlands and lowland deciduous forests (the Herb and Filicinae factors). Within ~1500 years, rainforest values dropped to levels comparable to or less than those of Holocene minima, values of thermophilous forest and semi-arid vegetation exceeded those of the Holocene, and subbandean *P. andina* rainforest reached lowest values of the entire record. Interglacial vegetation was not static. Representation of lowland deciduous forest fluctuated at or near initial interglacial levels in contrast with the high amplitude variations in the *N. dombeyi* rainforest. A brief expansion of precordilleran *P. andina* forest straddles the interglacial/stadial boundary.

The rapid increase in rainforest at 116 ka occurs at the midpoint of the MIS 5e/MIS 5d isotope transition and marks the end of interglacial deciduous forest. Thus, in southern Chile, both the end and the beginning of interglacial conditions coincide with those of MIS 5e. Within MIS 5d, changes in *N. dombeyi* rainforest and xeric open vegetation are minimal compared with those of Termination II. Values of both factors remain well above those of MIS 6, unlike the δ¹⁸O record in which near-glacial values are reached. *P. andina* forest, however, does decrease to glacial values, except for a small increase that coincides with that of δ¹⁸O at ~110 ka.

### Table 1

<table>
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<tr>
<th>N. dombeyi</th>
<th>P. andina</th>
<th>Filicinae</th>
<th>Herb</th>
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</thead>
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<td>0.9887</td>
<td>3.5000</td>
<td>-0.1841</td>
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<td>79.039</td>
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Fig. 3. Time series of pollen assemblages (N. dombeyi, P. andina, Herb, and Filicinae factors) and δ¹⁸O from OSP Site 1234 (Table 1). Marine isotope stages 1 and 5e (dark yellow) and 5 (light yellow) are highlighted.
The record of MIS 5c vegetation—a stepwise decrease in open deciduous forest and increase in rain forest—is distinguished by the rapid rise in pre-cordilleran *P. andina* rainforest that peaks just after the MIS 5e δ18O minimum at ~100 ka. Subsequently, trends of lowland deciduous forest and rainforest development generally correspond with negative and positive changes in ice volume, respectively; however, these two vegetation assemblages and δ18O are not always precisely in phase. In MIS5a, for example, deciduous forest nears interglacial values after the δ18O event. The staccato beat of *P. andina* punctuates the MIS 5a/MIS 4 transition. Two peaks, centered ~74 and ~68 ka, precede the late-stadal rise of rainforest and decrease in deciduous forest to full glacial values in MIS 4.

With the exception of a ~5–6 ka interval at the base of MIS 3, rainforest vegetation continued to blanket southern Chile. After a short interval of deciduous forest prominence at the beginning of MIS 3, representation of lowland deciduous forest was low, dropping to values below that of MIS 6 after ~40 ka. Three peaks of *P. andina* (~50, ~43, and ~37 ka) mark the end of MIS 3. In MIS 2, two lesser *P. andina* events (at ~28 and ~23 ka) preceded the abrupt end of rainfall dominance ≤17 ka. At the time of the 23 ka-event, the long decrease in lowland deciduous forest reversed, and values rapidly rose in step-like fashion to near-Holocene levels. The MIS 2/MIS1 deglacial pattern of *N. dombeyi* rainforest—a rapid initial decrease that tapers off gradually between ~15 and ~13 ka—resembles the beginning of the MIS 5 rainforest record. The *P. andina* record during Termination I is quite different. In Termination II, there is no counterpart to the robust peak of *P. andina* that occurs at ~13.5 ka. The Holocene begins with slight increase in the loadings of the Lowland Deciduous Forest Factor, which are less than those of MIS 5e and more like those of MIS 5c and MIS 5a. After a brief revival of rainforest (~9.5 ka), representation of all three forest assemblages approach those of the last interglacial.

There are no southern South American vegetation records with which the entire 145 ka pollen record from Site 1234 can be compared. Pollen data from the last 60 ka, the length of extant marine and terrestrial pollen records, show basic similarities in the response of vegetation to orbital- and millennial-scale patterns of climate change, as well as differences that reflect regional variations in the interplant between climate and vegetation of the pollen catchments of the two core sites (Fig. 1). Comparison between the pollen assemblages (factors) from ODP Site 1234 and ODP Site 1233, located ~5° south of Site 1234, shows the prominence of rainforests at both Sites throughout MIS 3 and MIS 2 (Fig. 4). Clearly, closed forests (*N. dombeyi*, and *N. dombeyi* along with *P. andina*) expanded throughout southern Chile. In the Rio Bueno drainage and throughout the Lake District, *N. dombeyi* forests dominated glacial vegetation (Heusser, 2003; Heusser, et al., 2006). Pollen data from Site 1234 reflect the steady expansion of cool, mesic *N. dombeyi* forest in the Bio Bio drainage between ~60 and ~35 ka and the subsequent rise to values of *N. dombeyi* rainforest approaching those in the south. The development of extensive *P. andina* rainforests in the northern ecotone during MIS 3 and MIS 2 ended at the glacial-interglacial transition, and was followed by a gradual reduction to the present status of *P. andina* as an endangered species. Abrupt contraction of *N. dombeyi*-dominated and *P. andina*-dominated rainforests at ~17.6 ka and the subsequent rise of open vegetation (Herb and Filicinae factors) represent the initial development of present-day lowland deciduous forest and Mediterranean-type vegetation in the north and that of Valdivian and North Patagonian Evergreen Forests in the south.

On land, Tagua Tagua is the only site from temperate South America with a continuous ~60 ka record. Located ~1.5° north of Site 1234 in subtropical Chile (Fig. 1), Tagua Tagua is presently surrounded by semi-arid, sclerophyllous woodland (Heusser, 1990). During MIS 3 and MIS 2, however, rainforest expanded into what is now subtropical Chile and the relative abundance of rainforest pollen (*N. dombeyi* and *P. andina*) often approached values from ODP Site 1234. During MIS 3, the pulsating abundance of *P. andina* implies frequent expansion of rainforest now restricted to the pre-cordilleran Andes into the central valley. In both sites, percentages of lowland forest (*N. obliqua*) are comparable in the beginning of MIS 3 and MIS 2 (Fig. 5). Later, the records of *N. obliqua* diverge, declining from maximum values at ~30 ka to Holocene minima in MIS 1 at Tagua Tagua, and increasing from minimal values during the last glacial maximum to maximum Holocene values in the south. After ~40 ka, values of *N. dombeyi* in the southern (Site 1233) record are consistently higher than those of the northern site. At the end of the last glacial, the northern and southern records diverge. The initial decrease in *N. dombeyi* at Tagua Tagua leads that of Site 1233 by ~2 ka, as does the late glacial rise in *P. andina*. This apparent north/south asynchrony in the latitudinal and altitudinal migration of plant communities represented in the Tagua Tagua and ODP Site 1234 records may reflect differential response to latitudinal variations in atmospheric circulation and snowline depression (Denton et al., 1999; Heusser, 1990). Undoubtedly, inadequate chronological control may also be a factor. Most of the Tagua Tagua record is beyond the range of radiocarbon and far beyond calendar corrections. After ~30 ka, it would appear that Tagua Tagua would be a bit older, and by 50 ka would be about 5 ka older than shown.

### 3.2. Paleoclimatic inferences

Climatic change is undoubtedly the driving factor in long-term vegetation dynamics in Chile, although volcanism, earthquakes, and other natural disturbances may be secondary controls (Veblen et al., 1992). The latitudinal and altitudinal migrations of deciduous and evergreen forests in southern Chile over the past 140 yr inferred from
Fig. 4. Time series of the *N. dombeyi*, *P. andina*, Herb, and Filicinae factors from ODP Site 1234 (dark green) and ODP Site 1233 (light green) for the last ~60 ka (Fig. 1), (Table 1)(Heusser et al., 2006). Marine isotope state 1 is highlighted.
ODP 1234 pollen data imply significant precipitation and, to a lesser extent, temperature change. Based on the present covariance between pollen/plant assemblages and climate variables in southern South America (Heusser, 2003), annual precipitation in the Bio drainage during the last glacial maximum may have been ~2000 mm higher, and

Fig. 5. Comparison of selected pollen data from ODP Site 1234 (dark green) and Laguna de Tagua Tagua, Chile (light green) for the last ~60 ka (Fig. 1). Percentages of Tagua Tagua taxa are based on a pollen sum that excluded Chenopodiaceae in order to reduce over-representation of locally produced chenopods (Heusser, 1990, 1994).
winter and summer temperatures ~ 5 and ~3°C lower, respectively.

It is apparent that, the configuration and tempo of change in the climatic ecotone of southern Chile monitored by ODP Site 1234 mirrors millennial-scale and orbital-scale regional and global climate change over the last 140 ka yr (Figs. 2–4) (Heusser, 2003; Moreno, 2004; Villa-Martinez et al., 2003). Climatic reconstructions from shorter sequences elsewhere in Chile resemble proxy climate signals from ODP 1234. At ~41°S, the prominence of open North Patagonian/subantarctic forests at the end of the last glacial suggested that summer temperatures (~8–9°C) and annual precipitation (~5000 mm) were similar to those now ~10° poleward (Heusser et al., 2006).

On the other side of the South Pacific at comparable latitudes, long-term climatic trends inferred from Tasmanian and New Zealand pollen records resemble those from Chile—an oscillating descent from the last interglacial, which was slightly warmer than the Holocene, to cold glacial conditions that terminated ~17 ka (Colhoun, 2000; Heusser and van de Geer, 1994; Vandergoes et al., 2005).

To the south, Antarctic records reflect orbital variations evident in the marine and terrestrial climate signals from Site 1234 (Blunier and Brook, 2001; Stenni et al., 2003). Canonical correlation of Antarctic ice core data and ODP Site 1233 terrestrial and marine records has shown that southern hemisphere climate variability are closely linked (Pisias et al., 2006). Spectral analysis of pollen and radiolarian taxa from ODP Site 1233 and Byrd ice core data suggest that millennial-scale climate variability during the past 75 ka in the Southeast Pacific is tightly coupled at periods longer than 3000 years (Heusser et al., 2006; Pisias et al., 2006).

Spectral comparison of the pollen Factor 1 (cool, mesic N. dombeyi rainforest) in Site 1234 with δ18O in the Byrd Ice core (Blunier and Brook, 2001), using traditional Blackman-Tukey methods in the well known ARAND package (Pisias, personal communication 2006), shows that most of the variance in the vegetation and climate of southern Chile during the last 140 ka lies in the so-called “Milankovitch” orbital bands with periods > ~19 ka (Fig. 6, top). On this glacial-interglacial scale, cool-moist conditions in central Chile were coherent with (Fig. 6, middle) and occurred in phase with (Fig. 6, bottom) Antarctic cooling. Note that with these short time series, the various orbital effects of precession, tilt, and eccentricity cannot be distinguished in the spectrum. Orbital periodicity in terrigenous proxies of the Mediterranean climate of central Chile from the last ~120 ka showed no significant phase difference between the proxies and the precession index (Lamy et al., 1998).

Significant coherency also exists in the millennial bands (especially near periods of ~7 and ~4 ka), but here the changes in the rainforest pollen assemblage from Site 1234 lag Antarctic cooling by ~30–90° (i.e., from ~300–1800 yr). Such a lag of the local vegetation and climate response at millennial scales in central Chile is consistent with lags of terrigenous mineral content at Site 1233 behind Antarctic climate, (Lamy et al., 2004). We note, however that there is no lag in the fern-dominated

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**Fig. 6.** Spectral and Cross Spectral comparison of Pollen Factor 1 (N. dombeyi and other rainforest taxa) with δ18O in the Byrd Ice Core (Blunier and Brook, 2001). Ice core data were multiplied by −1, so that higher values reflect colder conditions, for purposes of illustrating phase. The time series were interpolated to 0.5 kyr intervals, between 1 and 88 kyr, using Gaussian smoothing to remove variations of <1 kyr. Top—Power spectra of Byrd δ18O (black) and pollen Factor 1 (red); “bw” notes the bandwidth of 0.022 kyr−1. Middle—Coherency Spectrum; 80% significance level is 0.655. Bottom—Phase spectrum, with phase error bars and bandwidth noted. Phase estimates are only plotted (with bandwidth and error estimate) in frequency bands that are significantly coherent bands are plotted. Note that pollen Factor 1 and Antarctic cooling are in phase over the well-known Milankovitch orbital bands (in which individual components associated with eccentricity, tilt, and precession cannot be distinguished in these short time series), but that pollen lags Antarctic climate in the millennial bands with periods near ~7 and ~4 kyr. This pattern of lagging phases at higher frequencies can be simulated in a model with a single-exponential response time of 1 kyr (red line in bottom panel).
pollen assemblage from Site 1233 (Pisias, et al., 2006). This may reflect differential response of the two different pollen assemblages from ODP Site 1234 and 1233 to climate forcing, as well as possible age-model errors related to the lack of a common chronostratigraphy.

To a first approximation, the observed phase spectrum of pollen Factor 1A relative to the Byrd ice core can be predicted based on a simple model of exponential response time (red line in Fig. 6, bottom, in which phase = arctan(2π × τf), where τ is a single exponential time constant, and f is the frequency (Imbrie et al., 1984; Pisias et al., 1990), given an exponential response time on the order of 1000 years. Such a time constant may reflect differences in the response of ecosystems of southern and Central Chile to climate change.

4. Conclusion

Directly correlated, high-resolution pollen and benthic oxygen isotope data from ODP Site 1234 provide the first, continuous, chronostratigraphically controlled vegetational-environmental record from the last glacial cycle from temperate South America. Throughout the last 140 ka, the complex sequence of changes in Chilean vegetation and climate correspond with variations in global ice volume. At Termination II, rapid replacement of cool, hyperhumid glacial vegetation (N. dombeyi-dominated rainforests) and development of interglacial lowland deciduous forest occurred in phase with the decrease in global ice volume.

Warm, semi-arid conditions that continued after ice buildup in MIS 5d gradually deteriorated to near-glacial levels in MIS 5b. In MIS 5a, revived lowland deciduous forest development coincided with ice volume decrease both in timing and amplitude. Subsequent fluctuations in the overall decline of Mediterranean-type climate and northward expansion of humid, temperate climate parallel southern hemisphere δ18O records. During the last Full-glacial, the prominence of hyper-humid vegetation (North Patagonian and Subantarctic forests and parkland) implies sustained northward migration of the southern westerlies. Between ~17,000 and 35 ka, significant cooling events (inferred from the expansion of grass-dominated Subantarctic parkland) correspond with piedmont glacier lobe maxima. At Termination I, the abrupt decline of N. dombeyi-dominated rainforests and development of interglacial lowland deciduous forest occurs in phase with the rapid δ18O shift—exactly in the same manner as at the beginning of Termination II. However, the forests that developed during the present interglacial have a lower abundance of helophytes than those of the last interglacial, suggesting greater aridity and warmth during MIS 5e. A brief climate reversal, centered on ~14–12 ka, interrupted the unidirectional glacial/interglaciation transition.

Comparison to Antarctic ice core data suggests that glacial-interglacial advances of the Chilean rain forests occurred in phase with Antarctic cooling. On millennial scales, a lag of rainforest advance and retreat behind Antarctic cooling and warming suggests that these southern Chilean ecosystems respond to regional climate change with an exponential response time of about 1000 years.

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