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Covariability of the Southern Westerlies and atmospheric CO_2 during the Holocene

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ABSTRACT

A suite of mechanisms has been proposed to account for natural variations in atmospheric CO_2 during the Holocene; all of which have achieved limited success in reproducing the timing, direction, and magnitude of change. Recent modeling studies propose that changes in the latitudinal position and strength of the Southern Hemisphere Westerly Winds (SWW) can greatly influence large-scale ocean circulation and degassing of the deep ocean via changes in wind-driven upwelling in the Southern Ocean. The extent to which the hypothesized SWW–Southern Ocean coupled system could account for changes in atmospheric CO_2 is uncertain, because of a lack of observations on the behavior of the SWW in the past, the paucity of appropriate records of productivity changes in the Southern Ocean, and our limited understanding of the sensitivity of the Southern Ocean biological and/or physical system to SWW forcing. Here we report a reconstruction of the behavior of the SWW during the past 14 k.y. based on terrestrial ecosystem proxies from western Patagonia, South America. The reconstructed variations in the intensity of zonal flow correspond to the timing and structure of atmospheric CO_2 changes, and are consistent with the modeled magnitude of CO_2 changes induced by varying strengths of the SWW. The close match between data and models supports the view that the SWW–Southern Ocean coupled system underpins multimillennial CO_2 variations during the current interglacial and, possibly, during glacial cycles over the past 800 k.y.

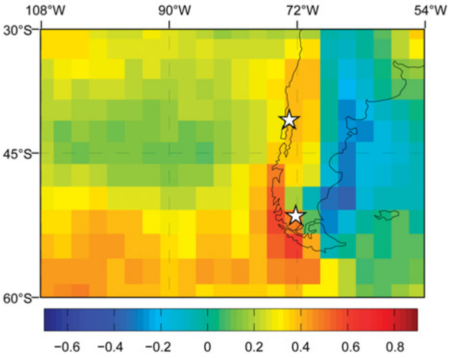

Figure 1. Map of South America showing location of Lago Guanaco and Lago Condorito (white stars), and local correlation of monthly NCEP (National Centers for Environmental Prediction, http://www.ncep.noaa.gov/) 700 hPa wind speed and Climate Prediction Center Merged Analysis of Precipitation (CMAP) enhanced precipitation anomalies. Positive correlations between wind and precipitation prevail along western margin of southern South America between 40° and 55°S, while correlations tend to be negative at similar latitudes along Atlantic coast.

INTRODUCTION: THE PROBLEM

High-resolution ice core records of atmospheric CO_2 variations feature a steady deglacial rise that reached a maximum of 268 ppmv (parts per million volume) ca. 11 ka (ka = 10^3 calendar yr ago), an ~8 ppmv reversal between 11 and 8 ka, and a steady multimillennial increase of ~25 ppmv since then (Indermühle et al., 1999; Monnin et al., 2004). Aspects of this pattern have been explained by means of sea surface temperature variations (Brovkin et al., 2008; Indermühle et al., 1999), large changes in terrestrial carbon reservoirs (Indermühle et al., 1999; Schurgers et al., 2006), ocean carbonate compensation (Ridgwell et al., 2003), and land use changes (Ruddiman, 2003); however, no single mechanism has been able to account for the timing and structure of natural atmospheric CO_2 changes during the Holocene. Toggweiler et al. (2006) proposed that changes in deep ocean ventilation in the Southern Ocean at the critical latitude of the Drake Passage (56°–61°S) can alter the CO_2 content of the atmosphere during glacial-interglacial transitions. Of particular importance are changes in the strength of the Southern Hemisphere Westerly Winds (SWW) at this latitude, which constitute a major driver of the Antarctic Circumpolar Current, the formation and overturning of North Atlantic Deep Water, and the upwelling of CO_2-rich deep waters. These changes in SWW strength can result from latitudinal shifts in the area of maximum zonal flow or changes in the intensity (surface wind speed) of westerly circulation.

STUDY AREA

The western region of southern South America (30°–55°S) offers some advantages for deciphering past variations in the SWW using terrestrial paleoclimate records and testing the hypothesized link between the SWW and atmospheric CO_2 because (1) it is the only continuous continental landmass that intersects the SWW from subtropical to subantarctic environments, including the regions of maximum SWW zonal flow (48°–50°S) and sectors of the Southern Ocean where deep ocean ventilation occurs; (2) there is a strong positive correlation between zonal wind speeds and local precipitation throughout the Pacific coast and Andean areas, thus validating the hemispheric-scale significance of paleoclimate inferences (Garreaud, 2007; Moy et al., 2008) (Fig. 1); (3) the Andes Cordillera establishes an effective barrier to the westward advection of moisture-laden air masses originating from the Atlantic, isolating the Andean regions and Pacific coast from such influence and allowing the distinction of changes in Atlantic or Pacific moisture sources; and (4) the climatically induced zonation of plant communities along latitudinal and altitudinal gradients provides a very sensitive biological system for detecting past variations in hydrologic balance inferred from palynological studies. Therefore, an array of sensitive paleoclimate records along a north-south transect through southern South America can be used track changes in the latitudinal position and strength of the SWW through time.

Most studies on the Holocene history of the SWW have focused on regions located north of the area of maximum wind speeds and annual precipitation in the subtropical region of southern South America (Maldonado and Villagrán, 2006; Villa-Martínez et al., 2003; Villagrán and Varela, 1990), and thus are pertinent for monitoring variations of its northern limit of influence (Fig. 1). A suite of studies in Tierra del Fuego and adjacent areas is relevant for determining changes near the southernmost margin of the SWW (Heusser, 1995; Markgraf, 1993; McCulloch and Davies, 2001). In this study we reconstruct changes in hydrologic balance from areas located south and north of the region of maximum zonal flow in central Patagonia (Fig. 1), changes that, in conjunction with proxies of paleofire occurrence in the western region of southern South America (>30°S) (Power et al., 2008), provide a coherent picture of SWW variations since 14 ka. Recent syntheses of paleofire activity in this region have emphasized

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the role of variations in the strength and location of the southeast Pacific subtropical high-pressure cell and the SWW in generating conditions conducive to fire occurrence. Changes in fire activity at centennial and millennial time scales are linked to persistent atmospheric and ocean circulation shifts that affect regional vegetation patterns, fuel conditions, and precipitation anomalies at subcontinental scale (Moreno, 2004; Whitlock et al., 2007).

We present high-resolution (~50 yr between samples), precisely dated pollen records from two small, closed-basin lakes located in the lowlands of southwest (Lago Guanaco, 51°S) and northwest Patagonia (Lago Condorito, 41°S) (Moreno, 2004) (Fig. 1). By virtue of their location, these sites are sensitive for monitoring changes in the transition between the Magellanic deciduous forest and Patagonian steppe and the north Patagonian and Valdivian rainforests, respectively (Moreno, 2004; Villa-Martínez and Moreno, 2007). Because the modern transitions between these plant communities involve changes in hydrologic balance driven by increasing amounts of precipitation of westerly origin, we interpret the relative dominance of Magellanic deciduous forest and the north Patagonian rainforest as evidence for relatively wetter conditions and increased influence of the SWW, and, conversely, the dominance of Patagonian steppe and Valdivian rainforest as indicative of relatively drier conditions and reduced effect of the SWW. We expect that persistent shifts in the latitudinal position of the SWW (equatorward or poleward) at multimillennial time scales should result in synchronous precipitation anomalies of opposite sign in the studied regions, whereas changes in the strength of zonal flow should result in simultaneous changes of the same sign (positive or negative precipitation anomalies).

RESULTS

Lago Guanaco is located near the modern forest-steppe ecotone in Torres del Paine National Park, southern Chile. This ecotone is a sensitive vegetation and climate boundary, marking the interface between the humid environments in the western Andean slope and the eastern semi-arid areas affected by the rain shadow effect of the Andean Cordillera (Villa-Martínez and Moreno, 2007). The floristic composition and geographic location of this ecotone are highly dependant on the amount and seasonality of westerly precipitation spilling eastward over the Andes. Thus, we expect that past eastward shifts of the forest-steppe ecotone should reflect increases in precipitation, and westward shifts should reflect decreases, in response to variations in the position or intensity of the SWW. We calculated a normalized *Nothofagus* (southern beech)/Poaceae (grass) index (NPI) based on the palynology of Lago Guanaco to illustrate past shifts of the forest-steppe ecotone (Moreno et al., 2009). Positive anomalies of the NPI represent the preeminence of southern beech scrublands and/or woodlands under wetter conditions, i.e., stronger SWW, and negative anomalies are indicative of the preponderance of Patagonian steppe under drier conditions, i.e., weaker SWW. The record from Lago Guanaco (Fig. 2) is constrained by 17 accelerator mass spectrometry (AMS) radiocarbon dates (see methods and data in the GSA Data Repository[1] Appendix 1) and shows dominance of Patagonian steppe grasses and forbs (Asteraceae) during the last glacial-interglacial transition, punctuated by a pulse of arboreal expansion at 12.3 ka that led to a maximum between 11.3 and 10.5 ka and NPI values approaching zero. A reversal in this trend ensued, along with a major increase in grasses and forbs that lasted until 7.8 ka; during this phase the NPI reached persistently negative values. A long-term trend toward arboreal dominance started at 7.8 ka, with centennial-scale fluctuations in southern beech, a prominent decline in grasses, and persistently

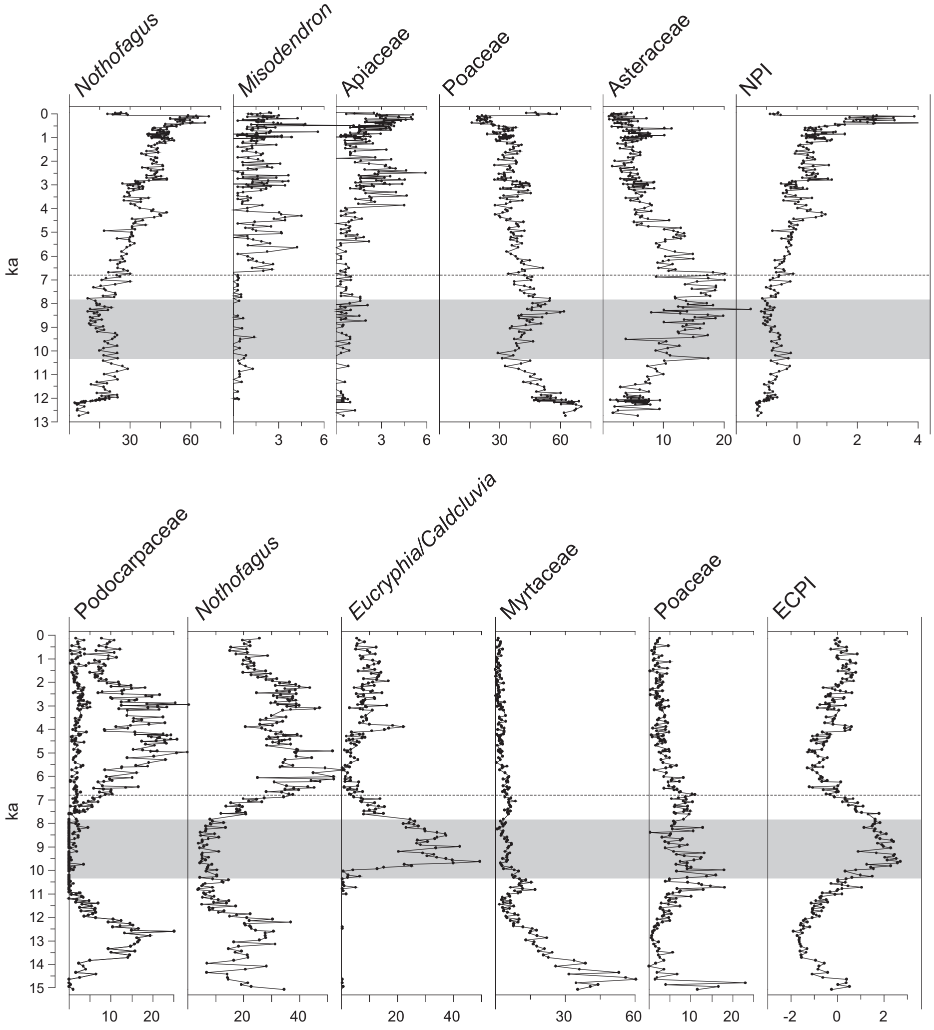

Figure 2. Simplified percentage pollen diagrams from Lago Guanaco (southwest Patagonia, upper panel) (see the Data Repository [see footnote 1]) and Lago Condorito (northwest Patagonia, lower panel) showing normalized *Nothofagus*/Poaceae index (NPI) and *Eucryphia* + *Caldcluvia*/podocarps index (ECPI). Podocarpaceae in Lago Condorito record includes species *Podocarpus nubigena* and *Saxegothaea conspicua*. Shaded bar spans synchronous, persistent multimillennial dry phase in southwest and northwest Patagonia between 10.4 and 7.8 ka. Dashed line at 6.8 ka indicates stabilization and point of no return in multimillennial trend toward arboreal dominance, increase in *Misodendron* and decline in Asteraceae in Lago Guanaco record, and time when ECPI values reach zero in Lago Condorito, i.e., balanced mix of north Patagonian and Valdivian rainforest taxa.

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[1] GSA Data Repository item 2010199, methods and supplementary stratigraphic/chronologic data, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

high values of forbs until 6.8 ka. These changes are expressed as variability superimposed on a trend toward positive NPI values. The southern beech rise then stabilized at 6.8 ka, and was accompanied by expansions of its parasite *Misodendron* and understory herbs (Apiaceae, possibly *Osmorhiza chilensis*). We interpret this sequence of events as a transformation from a grass to a scrub steppe, shifting to a southern beech scrubland, and then to the establishment of woodlands. Once established, this woodland underwent millennial-scale changes in its structure and spacial continuity (Moreno et al., 2009).

A pollen record from Lago Condorito shows the dominance of evergreen rainforests in the lowlands of northwest Patagonia over the past 15 k.y. (Fig. 2), with important variations in the abundance of Valdivian rainforest trees (*Eucryphia* + *Caldcluvia*) and north Patagonian rainforest podocarps (Moreno, 2004). The calculated *Eucryphia* + *Caldcluvia*/podocarp index (ECPI) illustrates the relative position of a fossil pollen sample along a gradient ranging from warm-temperate, seasonally dry climate characteristic of regions that are not influenced by the moisture-laden SWW for part of the year, and cool-temperate regions under the persistent influence of the SWW (Moreno, 2004). Negative anomalies in the ECPI indicate dominance of north Patagonian rainforests with the implication of cool-temperate and/or wet conditions and enhanced SWW, and positive anomalies indicate predominance of Valdivian rainforests under relatively warmer and drier climate, with reduced SWW influence. The Lago Condorito pollen record is constrained by 18 AMS radiocarbon dates (Moreno, 2004) and shows dominance of North Patagonian rainforests along with negative ECPI anomalies between 15 and 11 ka. A transitional phase featuring diversification of the pollen assemblage with plants having broad distributions in climate space (Moreno, 2004) and a consistent trend toward positive ECPI values occurred between 11 and 10 ka. Valdivian rainforests expanded rapidly and reached high abundance between 10 and 7.6 ka, with strong positive ECPI. Cool-wet north Patagonian trees (*Nothofagus*, *Drimys*, podocarps) expanded at 7.6 ka and attained high abundance until 3 ka, pushing the ECPI back to negative anomalies. A reexpansion of *Eucryphia* + *Caldcluvia* at 5 ka led to the establishment of a mosaic of Valdivian and north Patagonian rainforests characteristic of the modern lowlands of northwest Patagonia, forcing the ECPI values toward zero.

We compare our estimates of SWW activity with regional reconstructions of paleofires in the western region of southern South America (>30°S) since 14 ka (Fig. 3) (Power et al., 2008). When averaged at 500 yr non-overlapping time steps over this broad geographic scale, the standardized and transformed charcoal data indicate strong and persistent positive anomalies between 11 and 7.5 ka, followed by a steady decline between 7 and 3.5 ka that led to strong negative anomalies, a prominent rise at 3 ka, and values approaching the preindustrial average since then. A geographic analysis of the occurrence of paleofires (Whitlock et al., 2007) revealed that northwest and southwest Patagonia underwent peak fire activity between 12 and 9.5 ka, followed by a decline and latitudinal differentiation in fire regimes and a spatially heterogeneous increase after 6 ka.

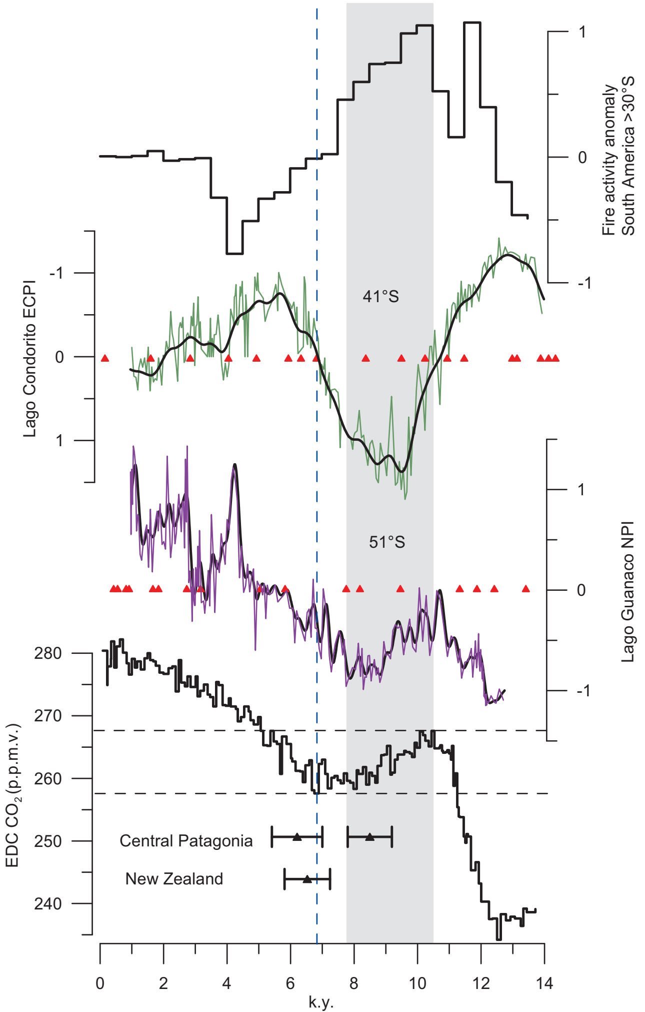

Figure 3. Comparison of Lago Guanaco *Nothofagus*/Poaceae (NPI) and Lago Condorito *Eucryphia* + *Caldcluvia*/podocarps (ECPI) with summary of paleofire activity in western region of southern South America (WSSA, >30°S; top diagram), atmospheric CO$_2$ data from EPICA (European Project for Ice Coring in Antarctica, http://www.esf.org/index.php?id=855) Dome C (Monnin et al., 2004) (lower diagram), and timing for commencement of Neoglacial advances in central Patagonia and Southern Alps of New Zealand (black triangles with error bars symbolizing 95% confidence intervals) (p.p.m.v.—parts per million volume). Red triangles in both pollen records represent supporting radiocarbon dates, and thick black lines represent single spectral analysis applied to raw index values (Moreno et al., 2009). We truncated the age scale over interval 14–1 ka to focus analysis on range of $\pm 1.5\sigma$ of variability. Gray bar brackets negative anomalies in NPI and ECPI between ca. 10.5 and 7.8 ka that coincide with peak fire activity in WSSA >30°S and reversal in atmospheric CO$_2$ record. Dashed blue line highlights timing of arboreal expansion and decline in Asteraceae in Lago Guanaco record, following series of short-term fluctuations at end of NPI minimum.

DISCUSSION AND CONCLUSIONS

The tight covariability of moisture changes and paleofires in areas located north and south of the region of maximum westerly flow suggests changes in the intensity of the SWW with conditions at or above the average between ca. 14 and 10.5 ka, reduced SWW influence between ca.10.5 and 7.8 ka, and a sustained increase afterward (Fig. 3). Our findings, while in broad agreement with previous studies along the western region of southern South America (30°–56°S), improve upon them by providing detailed high-resolution data from sites located in sensitive regions to monitor past variations in the SWW. Furthermore, the strengthening of the SWW that started at 7.8 ka and stabilized at 6.8 ka correlates, within dating uncertainties, with the commencement of neoglacial advances as early as 8.5 ± 0.7 ka and 6.2 ± 0.8 ka in central Patagonia (46°S) (Douglass et al., 2005) and at 6.5 ± 0.7 ka in New Zealand's South Island (43°S) (Schaefer et al., 2009) (uncertainties at the 95% confidence level in both cases), suggesting a Pacific-wide response of mountain glaciers to cooler temperatures and/or increased precipitation. Notable exceptions to this pattern are the paleoclimate estimates from deep-sea cores offshore northwest Patagonia (Lamy et al., 2001) and the chronology of raised shorelines in Lago Cardiel (49°S) (Gilli et al., 2001). These discrepancies could reflect, in the deep-sea cores, the unconstrained assumption of constant marine reservoir ages during the Holocene and/

or lack of climatic sensitivity of the iron intensity data, and in Lago Cardiel could reflect the fact that the lake is located in the extra-Andean region of central Patagonia, thus making it vulnerable to multiple moisture sources including westerly, Atlantic, and polar outbreaks.

The close correspondence between changes in the intensity of the SWW and atmospheric CO_2 variations since 14 ka (Fig. 3) lends empirical support to the idea that changes in the surface stress of the SWW on the Southern Ocean have been a key factor controlling CO_2 fluxes from the deep ocean to the atmosphere during the Holocene. The magnitudes of these excursions (8–25 ppmv) are within the range of modeled CO_2 variations forced by a 50% variation in wind strength (Tschumi et al., 2008). Weaker SWW between ca. 10.5 and 7.8 ka might have resulted from a reduction in latitudinal temperature gradients, driven by negative anomalies in mean annual insolation in the tropics coupled with positive anomalies in mean annual insolation in the high southern latitudes in response to greater-than-present obliquity (Whitlock et al., 2007). We speculate that the SWW–Southern Ocean coupled system could also be responsible for similar atmospheric CO_2 excursions that have taken place repeatedly since 800 ka (Luthi et al., 2008; Anderson et al., 2009). The interaction of these SWW-forced greenhouse gas excursions (Toggweiler et al., 2006) with other sources of climatic variability, past a certain threshold, could establish a positive feedback that might underlie global temperature changes during glacial cycles.

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