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Radiocarbon chronology of the last glacial maximum and its termination in northwestern Patagonia

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ABSTRACT

We examine the timing and magnitude of the last glacial maximum (LGM) and the last glacial termination (LGT) in northwestern Patagonia, situated in the middle latitudes of South America. Our data indicate that the main phase of the LGT began with abrupt warm pulses at 17,800 and 17,100 cal yrs BP, accompanied by rapid establishment of evergreen temperate rainforests and extensive deglaciation of the Andes within 1000 years. This response shows that South American middle-latitude temperatures had approached average interglacial values by 16,800 cal yrs BP. The temperature rise in northwestern Patagonia coincides with the beginning of major warming and glacier recession in the Southern Alps of New Zealand at southern mid-latitudes on the opposite side of the Pacific Ocean. From this correspondence, the warming that began at 17,800 cal yrs BP appears to have been widespread in middle latitudes of the Southern Hemisphere, accounting for at least 75% of the total temperature recovery from the LGM to the Holocene. Moreover, this warming pulse is coeval with the first half of the Heinrich Stadial 1 (HS1) in the North Atlantic region. HS1 featured a decline of North Atlantic meridional overturning circulation, a southward shift of the westerly wind belt in both hemispheres and of the Intertropical Convergence Zone, as well as a weakening of the Asian monsoon. Along with the initiating trigger, identifying the mechanisms whereby these opposing climate signals in the two polar hemispheres interacted —whether through an oceanic or an atmospheric bipolar seesaw, or both— lies at the heart of understanding the LGT.

1. Introduction

Terminations of ~100,000-year glacial cycles represent the largest natural climate changes of late-Quaternary time. Terminations set the overall timing of these cycles by disrupting the evolution of the global climate system toward extreme glacial conditions. They feature melting of huge continental ice sheets situated in the Northern Hemisphere, together with reorganization of the global ocean-atmosphere system from a glacial to an interglacial mode. Deciphering the mechanisms responsible for terminations is thus prerequisite for understanding the causes of ~100,000-year glacial cycles. Discussion of this topic has centered largely on the phasing relationships of climate events revealed in polar ice cores, which show interhemispheric asynchrony in the millennial bandwidth (Members, 2015). The extent to which these ice-core records are representative of climate change in extra-polar areas is insufficiently understood. To address this problem, we present radiocarbon-dated terrestrial stratigraphic records from northwestern Patagonia and compare them with the glacier and vegetation record in the Southern Alps of New Zealand, both situated in southern middle latitudes. Precisely dated stratigraphic records from the southern middle latitudes afford a test of the hemispheric-scale significance of the climate signature of Antarctic

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ice cores, and may clarify the relative roles of changes in deep-water circulation and/or shifts in major wind belts for the initiation and propagation of abrupt climate changes at global scales, including those associated with the last glacial termination (LGT).

Our radiocarbon-dated palynologic and glacial geologic records come from the lowlands of northwestern Patagonia in the Chilean Lake District, Isla Grande de Chiloé and on the adjacent Chiloé Continental sector (Fig. 1). Our collation of new and published AMS (Accelerator Mass Spectrometry) ^{14}C-dated terrestrial records allows us to define the timing and sequence of events during the last glacial maximum (LGM) and the LGT in the middle latitudes alongside the southeastern Pacific Ocean. Our aim is to examine the intra- and inter-hemispheric phasing of paleoclimate signals during the LGT. For that purpose we developed a master pollen stratigraphy that combines the palynology and associated radiocarbon dates from sites with high-resolution records, together with radiocarbon-dated volcanic and glacial deposits and geomorphic features that are key to deciphering the timing and extent of Andean ice lobes during the LGM and the LGT. Our radiocarbon chronology relies on terrestrial samples, which directly monitor the radiocarbon content of the atmosphere, thus circumventing the uncertainties of changing marine reservoir corrections.

2. Setting

Northwestern Patagonia (40°–44°S) features the Chilean Lake District and the Chilotan archipelago, most noteworthy Isla Grande de Chiloé (Fig. 1). It is bounded by the Andes Cordillera in the Chiloé Continental sector in the east and by the Coastal Range in the west that runs along a north-to-south axis adjacent to the southeastern sector of the Pacific Ocean. The overall cordillera attains its highest altitudes between 15° and 35°S, with maximum elevations declining steadily toward the south (~2500 m.a.s.l. at 35°S, ~1800 m.a.s.l. at 40°S, and ~1400 m.a.s.l. at 45°S). Abundant precipitation delivered by westerly winds coupled with adiabatic cooling allows the occurrence of more than 35 isolated glaciers on the highest peaks between 35° and 45°30′S (Lliboutry, 1998), most of them volcanoes. Cirque glaciers become increasingly common poleward of 41°S, followed south of 45°30′S by numerous mountain glaciers, outlet glaciers, and ice fields, including the Northern and Southern Patagonian Ice Fields. The calculated equilibrium line altitude declines poleward from elevations of ~3300 m.a.s.l. at 35°S, to ~2300 m.a.s.l. at 40°S, to a minimum of ~600 m.a.s.l. at 52°S (Condom et al., 2007).

Northwestern Patagonia is under the influence of explosive eruptions from several volcanoes in the Southern Andean Volcanic Zone. This volcanism results from the subduction of the Nazca Plate beneath the westward moving South American Plate (Stern, 2004), along a narrow volcanic arc that follows the Liquiñe-Ofqui fault system in Chile between 33° and 46°S. The Southern Andean Volcanic Zone includes at least 60 active or potentially active volcanoes in Chile and Argentina, as well as three caldera systems and numerous minor eruptive centers (Stern, 2004). Several active volcanoes have historic explosive records. The most relevant are Mocho-Choshuenco (39°55′39″S, 72°1′37″W), Lanín (39°37′58″S, 71°29′59″W), Grupo Antillanca (40°46′15″S, 72°9′12″W), Osorno (41°6′0″S, 72°29′35″W), the recently erupted Puyehue-Cordón Caulle (40°35′25″S, 72°7′2″W) and Volcán Chaitén (42°49′58″S, 72°38′45″W) on years 2011 and 2008 respectively, and the currently active Volcán Villarrica (39°25′0″S, 71°56′0″W) and V. Calbuco (41°19′34″S, 72°36′52″W).

Precipitation of westerly origin occurs throughout the year in northwestern Patagonia, with variations in frontal activity resulting from latitudinal shifts of storm tracks at seasonal and interannual scales (Garreaud et al., 2013). The seasonality of precipitation increases north of 41°S, along with a rise in continentality caused by the rain-shadow effect of the Coastal Range on the Longitudinal Valley, a broad north-south oriented tectonic depression situated between the Coastal Range and the Andes Cordillera. The zone of maximum precipitation (48°–50°S in central Patagonia) shifts north/south during the winter/summer months, respectively, along with latitudinal sea-surface temperature gradients and the interaction between the subtropical Pacific high-pressure cell and the polar low-pressure belt (Aceituno et al., 1993; Garreaud et al., 2013; Quintana and Aceituno, 2012).

The temperate high-rainfall regime in northwestern Patagonia fosters broadleaved temperate rainforests, which closely follow altitudinal and latitudinal climate gradients in temperature and precipitation from sea level up to the treeline (1000–1200 m.a.s.l.). The upper treeline represents a major discontinuity in the distribution of arboreal species in the cold, wet, and wind-swept environments of the high Andes of Patagonia. A study of the spatial and temporal variation in *Nothofagus pumilio* growth at treeline along its latitudinal range (35°40′S-55°S) in the Chilean Andes (Lara et al., 2005) showed that (i) temperature has a spatially larger control on tree growth than precipitation, and that (ii) this influence is particularly significant in the temperate Andes (>40°S). These results suggest that low temperatures are the main limiting factor for the occurrence of woodlands and forests at high elevations in the Andes, considering that precipitation increases with elevation at any given latitude (Lara et al., 2005).

The temperate rainforests in northwestern Patagonia are dominated or co-dominated by species of the genus *Nothofagus*, the Southern Beech. These rainforests occur from sea level onto the humid slopes of the western flanks of the Andes and Coastal Range (Fig. 1) (Villagrán, 1985, 1988a, b). Between 40° and 43°S, three main forest communities have been distinguished on the basis of their floristic composition: Valdivian, North Patagonian, and Subantarctic. The evergreen Valdivian rainforest, the most biodiverse and heterogeneous in terms of canopy structure, occupies low-elevation sectors in relatively warm areas with strong precipitation seasonality and inter-annual variability in the northern part of this region. Important pollen indicators characterize the modern pollen rain of this forest community, among them are the trees *Eucryphia cordifolia* and *Caldcluvia paniculata*, accompanied by numerous other trees, shrubs, epiphytes, and vines. North Patagonian evergreen rainforests supersede or intermingle with Valdivian communities under colder/wetter conditions, either upslope in the mountain ranges in northwestern Patagonia or in areas south of 41°S. The Valdivian and North Patagonian communities share many species, the latter having lower biodiversity and a simpler canopy structure, together with the presence and occasional dominance of cold-resistant conifers (*Podocarpus nubigena*, *Saxegothaea conspicua*, *Fitzroya cupressoides*, and *Pilgerodendron uviferum*) at higher elevations (550–850 m.a.s.l.) and in Isla Grande de Chiloé. Deciduous Subantarctic forests dominate sub-alpine environments subject to seasonal snow cover under cold, wet, and windy conditions. The broad latitudinal distribution of the Subantarctic forest community throughout western Patagonia reflects its ability to withstand extreme temperature conditions. These winter-deciduous forests establish a transition between the evergreen rainforests discussed above and the Patagonian Steppe east of the Andes, and the High Andean plant communities located above the treeline. The dominant species in Subantarctic forests is *N. pumilio*, which may form monospecific stands and present a species-poor understory. *N. pumilio* forests intermingle with *Nothofagus betuloides* in more humid sectors, establishing a mosaic with evergreen forests. In palynological terms, this plant community can be traced by assemblages having an arboreal component dominated almost exclusively by *Nothofagus* pollen, lacking epiphytes and vines, and