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Quantifying climate change in Huelmo mire (Chile, Northwestern Patagonia) during the Last Glacial Termination using a newly developed chironomid-based temperature model

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A B S T R A C T

The development of quantitative temperature reconstructions in regions of paleoclimate interest is an important step for providing reliable temperature estimates in that region. Fossil chironomid assemblages have been studied in Patagonia showing great promise for reconstructing paleotemperatures; however there is still a lack of robust temperature inference models in that area.

To contribute to the understanding of climate change, a transfer function using chironomids preserved in 46 lakes in Chile and Argentina was developed. The best performing model to infer the mean air temperature of the warmest month was a 3-component WA-PLS model with a coefficient of correlation (r^2_{jack}) of 0.56, a root mean square error of prediction (RMSEP) of 1.69 °C and a maximum bias of 2.07 °C. This model was applied to the chironomids preserved in the sediment of the Huelmo mire (41°31′ S, 73°00′ W), in the lake district of northwestern Patagonia. The reconstruction showed several cold spells (one at 13,200 to 13,000 cal yr BP and a cooling trend between 12,600 and 11,500 cal yr BP) associated with the Younger Dryas and/or Huelmo–Mascardi Cold Reversal (HMCR). Our findings support climate models proposing fast acting inter-hemispheric coupling mechanisms including the recently proposed bipolar atmospheric and/or bipolar ocean teleconnections rather than a bipolar see-saw model.

1. Introduction

Patagonia is an important area for paleoclimate studies in southern South America because it is significant in understanding climate synchronization between the North and South Hemispheres. However, views are still polarized concerning climate dynamics during key periods of large-scale climate fluctuations (e.g. the Lateglacial/Holocene transition) (Whitlock et al., 2006; Rojas et al., 2009; Killian and Lamy, 2012). Despite efforts to identify climate fluctuations after the Last Glacial Maximum (LGM), the timing and extent of a cold reversal contemporaneous to the Younger Dryas (YD) is still in unresolved. Divergent evidence comes from paleoclimate studies based mainly on terrestrial records from the Andean Patagonian forest of Chile and Argentina. These studies show either i) a cooling pattern synchronous with the YD (12,500 to 11,200 cal yr BP) (Heusser et al., 1996; Ariztegui et al., 1997; Moreno, 1997, 2004; Moreno et al., 2001; Massaferro and Brooks, 2002); ii) a cooling pattern synchronous with the Antarctic Cold Reversal (ACR, 14,500 to 13,000 cal yr BP) (Lamy et al., 2004; Moreno et al., 2009); or iii) an intermediate YD/ACR climate signal called Huelmo–Mascardi Cold Reversal (HMCR, 13,500 to 11,600 cal yr BP) (Hajdas et al., 2003; Bertrand et al., 2008b; Massaferro et al., 2009). Differences between these records may be attributed to the individual response of proxies, chronological control, sampling resolution, individual site characteristics, the differential influence of the Southern Westerly Winds (SWW) on the east or west side of the Andes or merely because the signature of the cold event in the southern hemisphere is weak. In New Zealand, similar discrepancies were apparent during the Late Glacial/Holocene transition (Denton and Hendy, 1994; Newnham et al., 2003; Turney et al., 2003; McGlone et al., 2004). Resolving this problem is important for understanding the intra- and inter-hemispheric modes of millennial-scale climate changes during the Last Glacial Termination, and for determining the

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climatic mechanisms involved in their initiation and propagation. Production of quantitative, high resolution reconstructions of summer temperature will be particularly important in this respect. To contribute to the resolution of this problem we have used chironomids to obtain a summer temperature reconstruction, the first of its kind in northern Patagonia, from a Late Glacial lake sediment sequence.

Summer temperature is one of the major controls over the chironomid life cycle (Rossaro, 1991; Brodersen and Lindegaard, 1999) and many models (transfer functions) have been developed in the Northern Hemisphere to quantify summer temperature (e.g. Walker et al., 1991; Olander et al., 1999; Brooks and Birks, 2001; Larocque et al., 2001, 2006; Self et al., 2011; Eggermont and Heiri, 2012). In the southern Hemisphere, transfer functions have been developed for southern Patagonia (Massaferro and Larocque, 2013), northern Chile (Araneda et al., in prep), Tasmania (Rees et al., 2008) and New Zealand (Dieffenbacher-Krall et al., 2007; Woodward and Shulmeister, 2007) showing the potential of using chironomids in this region for temperature reconstruction. Even though northern Patagonian paleoenvironmental investigations using chironomids are not numerous, there are several qualitative and semiquantitative records indicating that changes have occurred in this faunal community during the Late Glacial period (Massaferro and Brooks, 2002; Massaferro et al., 2009). A recent quantitative reconstruction at Potrok Aike, in southern Patagonia, confirms the potential of chironomids to help in understanding the complex climate fluctuations in southern South America (Massaferro and Larocque, 2013).

In this paper, we present the first quantitative chironomid-inferred temperature model for Northern Patagonia (Argentina and Chile) and use it to reconstruct temperatures during the Late Glacial from a fossil chironomid record from Huelmo mire, located in Chilean Patagonia at 41° S. An earlier qualitative analysis of chironomids and pollen from Huelmo indicated temperature and precipitation changes between ca. 20 and 10 cal kyr BP (Massaferro et al., 2009). The chironomid and pollen records from Huelmo indicated step-wise deglacial warming beginning at ca. 18,000 cal yr BP, in agreement with other paleoclimate records from northwestern Patagonia, and ice core records from Antarctica (Pedro et al., 2011). Isotopic signals from Antarctic ice cores indicate relatively warm conditions between ~15,000 and 14,000 cal yr BP, followed by a reversal in trend with cooling pulses at ~14,000 and 13,500 cal yr BP, and warming at the beginning of the Holocene (Jouzel et al., 2003) Peak warmth during the Last Glacial Termination was achieved during ~14,500 cal yr BP, followed by a cooling trend that commenced during the ACR (~14,000 cal yr BP), which later intensified and persisted during the so-called Huelmo–Mascardi Cold Reversal (HMCR) (Hajdas et al., 2003; Massaferro et al., 2009). A reconstruction of temperature using chironomids will quantify the warmer and colder periods suggested by the previous pollen and chironomid records.

2. Site location

The Huelmo mire (41°31′ S, 73°00′ W) is located in the lowlands of the southern Chilean Lake District, on the western side of Seno Reloncaví (Fig. 1). The area is characterized by a mix of Valdivian, North Patagonian and temperate rainforest vegetation. The area that surrounds Huelmo has been altered by human activities. Current vegetation close to the mire is heavily influenced by clearance, leaving grassland for grazing. Quaternary glacial, volcanic, eolian and alluvial–colluvial deposits cover most of the bedrock geology in the area (Heusser, 1999).

At Puerto Mont, on the northern shore of Seno Reloncaví, mean annual temperature is 11.2 °C (ranging from 7.7 °C in winter to 15.1 °C in summer) and mean annual precipitation is 2341 mm (Moreno and Leon, 2003). This cool-temperate, wet climate results from the cold, offshore Humboldt Current combined with the Southern Westerly Winds (SWW) (Garreaud et al., 2009).

3. Material and methods

3.1. Sampling, stratigraphy and chronology

Several overlapping sediment cores from the center of the Huelmo mire were extracted using a square-rod Livingstone corer. For this study, cores 601A, 990-1A and 990-1B were combined in a 421 cm long composite sequence spanning the time interval between 19,600 and 10,000 cal yr BP (1071–650 cm). Stratigraphic correlation between these cores was achieved using loss-on-ignition records and two prominent tephra layers (Moreno and Leon, 2003). The stratigraphy of the composite core consisted of a floor of sand and gravel grading to silt with increasing amounts of organic material. On top of this, there was a sequence of organic gyttja, a thick sand volcanic ash layer, coarse organic detritus with gyttja and woody peat on top. The chronology of the core was based on 37 AMS radiocarbon dates, which were converted to calendar yr BP using CALIB 4.1.2 (Stuiver et al., 2005). The age–depth curve reveals continuous sedimentation along the time span of the composite core (Fig. 2). More details about lithology and age model are discussed in Moreno and Leon (2003).

The core stratigraphy together with the age–depth curves, X-radiographs and loss-on-ignition data indicate a major change in depositional patterns above and below a prominent volcanic ash at 696 cm depth (interpolated age of 11,000 cal yr BP). Before this ash layer, pelagic sedimentation prevailed indicating the presence of a permanent lake. After the tephra deposition, the Huelmo site underwent a rapid drop in lake-level and the expansion of a swamp (indicated by a shift to coarse detritus gyttja/woody peat) (Moreno and Leon, 2003).

3.2. Training set lakes

Thirty lakes were sampled during the austral summer of 2000 and 2002, six of them are located in Chile and twenty-four in Argentina, along an altitudinal gradient of 72.4 to 1925 m a.s.l., between 39° to 43° S and 70° to 73° W (Table 1). An additional 16 lakes from Argentina were incorporated into the training set in 2007 in order to increase the temperature gradient. Each lake was sampled using a mini-Renberg gravity corer (the first 30 lakes) or a Hongve-style gravity corer (the remaining 16 lakes) to preserve the sediment–water interface and the top 2–3 cm of the sediment was taken. Ninety percent of the sampled sites were located in areas with minimal human disturbance, such as national parks and nature reserves. Most of the high altitudinal lakes were located above the treeline in remote and pristine areas of Argentina. The environment encircling the lakes was similar on both sides of the Andes. Northern Patagonia is a lake district in both Argentina and Chile and the vegetation is composed of a mix of Valdivian, evergreen and temperate forest elements.

A range of environmental variables (secchi depth, conductivity, surface temperature, total dissolved solids and pH) were measured for each lake. Mean annual air temperature (MAT), mean annual precipitation (MAP), mean temperature of the three warmest months (WMM) and mean temperature of the three coldest months (CMM) were obtained from the BRIDGE gridded data (New et al., 2002). Altitude and depth were also included in the training set. The surface water temperature gradient was 6.0–20.5 °C and mean summer air temperature ranged from 8.9 to 17.5 °C. The pH varied from 4.0 to 8.4 and conductivity from 0.14 to 126 μS.

All of the studied lakes are oligotrophic or hyperoligotrophic (Balseiro et al., 2004; Callieri et al., 2007; Diaz et al., 2007); thus nutrient content, phosphorus and chlorophyll a are below detection levels. As these systems are nutrient-poor, most are expected to be oxygen-rich, thus oxygen is not likely to be significant in explaining the distribution and abundance of chironomids in these lakes.