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Using a newly developed chironomid transfer function for reconstructing mean annual air temperature at Lake Potrok Aike, Patagonia, Argentina

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ABSTRACT

In the Southern Hemisphere, the lack of quantitative temperature records hampers the understanding of climate change since the Last Glaciation and refrains the comparison with the Northern Hemisphere records. To provide quantitative data, a 63-lake chironomid transfer functions was developed in Patagonia. Mean annual air temperature (MAT) was one of the most important factors explaining the distribution of chironomids while precipitation did not have any significant relationship with chironomid assemblages. The MAT model had a r^2 of 0.64, a RMSE of 0.83 and a maximum bias of 1.81 °C, comparable to other transfer functions of this size. This model was applied to the Lake Potrok Aike (PTA) chironomid records which consisted of only four taxa (*Phaenopsectra*, *Cricotopus*, *Smittia* and *Polypedilum*). The chironomid-inferred air temperatures were colder-than-the-average (10.8 °C) during the Lateglacial with the coldest temperatures (9 °C in average) during the Antarctic Cold Reversal (ACR). Between ca. 8000 and 3500 cal. years BP, the chironomid-inferred air temperatures were warmer-than-the-average with a decreasing trend. From ca. 3500 cal. years BP to the present, the chironomid-inferred temperatures oscillated around the average. The difference between the chironomid-inferred air temperature in the surface sample and the climate normal (1961–1990) was 0.6 °C, suggesting that chironomids are sensitive enough to quantitatively reconstruct MAT at PTA. The general pattern of temperature changes reconstructed by the PTA chironomid record corresponded well to other quantitative records in the Southern Hemisphere. The results presented here show that investing in the development of chironomid transfer functions for quantitative climate research in the Southern Hemisphere is valuable.

1. Introduction

The relationships between deglacial climate change in the Northern and Southern Hemispheres remain blurred by uncertainties in the absolute timing and magnitude of the events recorded in the two hemispheres. The uncertainties are greatest in the Southern Hemisphere mid-latitudes where few well-dated, high-resolution records are available for comparison with the records derived from sites located in Antarctica and in the Northern Hemisphere. In particular, the presence of a cold event similar to the Younger Dryas (YD) in South America has been debated for more than a decade. The discussion is mainly based on conflicting results from pollen and beetle studies from the Andean region south of 40°S (Bennett et al., 2000; Heusser, 1993; Heusser and Rabassa, 1987; Hoganson and Ashworth, 1992; Markgraf, 1991, 1993) in the glacial times. Recent studies of Antarctic ice cores (Pedro et al., 2011; Petit et al., 1999) have stimulated the discussion but did not resolve the controversy as these results point toward asynchrony events between Antarctic sites (Blunier and Brook, 2001; Steig et al., 1998). Only details about the timing and magnitude of climate change from underrepresented areas in the Southern Hemisphere will clarify the relationships between the Northern and Southern Hemisphere, and thus identify possible coupling mechanisms.

The close relationship between air and water temperature and the distribution/abundance of chironomid larvae in Europe and North America has been used to develop inference models that can produce quantitative temperature reconstructions (reviews in Brooks, 2006; Walker and Cwynar, 2006). Air temperature reconstructions using chironomid assemblages have played an important role in NW Europe in recent attempts to reconstruct timing, magnitude and rates of climate changes during the Lateglacial–glacial/Interglacial Transition and the Holocene (Lang et al., 2010; Larocque-Tobler et al., 2010). The comparisons between chironomid-inferred air temperature records have allowed to determine temperature gradients across the Alps during the Lateglacial and early Holocene (Samartin et al., in press). Aquatic

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organisms, such as chironomids and diatoms, having a short life cycle might be more sensitive to climatic changes than long-lived terrestrial organisms (trees producing pollen), although all responded similarly to strong climatic changes (Birks and Ammann, 2000). The accuracy of quantitative paleoclimatic inferences from pollen may be compromised by long-distance pollen transport (Birks, 1981; Davis and Botkin, 1985). In Northern Sweden, chironomids have been shown to respond to early Holocene climate while diatoms were responding to changes in pH (Larocque and Bigler, 2004). Comparisons between chironomid-inferred temperatures and instrumental data have shown that inferences were accurate (difference between inferences and temperature of 0.6 °C in average) (Larocque and Hall, 2003; Larocque et al., 2009). Comparisons between diatom-inferred temperatures and instrumental data were again impaired by changes in pH (Bigler and Hall, 2003).

In Patagonia, chironomids are emerging as a new proxy indicator for climate (precipitation and temperature) change (Massaferro, 2010; Massaferro and Brooks, 2002; Massaferro et al., 2005, 2009). The record from Laguna Stibnite (46°S), situated to the west of the North Patagonian icecap, shows millennial scale changes in chironomid faunas which were interpreted as a response to fluctuations in rainfall regimes and associated lake level changes, driven by latitudinal migration of the South West Winds (SWW) (Massaferro and Brooks, 2002). Results from the Huelmo site in Chile provided new evidence associated with climate cooling during the Lateglacial–glacial. At the Huelmo site similarities between the pollen curves of cold resistant *Nothofagus dombeyi*, *Podocarpus nubigena* and the chironomid curves of *Rhietia*, *Paratanytarsus 1* and *Tanytarsus 1C* suggest that these chironomids may be cold temperature indicators. Chironomid assemblages from Huelmo also indicated that the cooling trend, starting at ca. 14,400 cal. years BP, corresponds with the timing of the Antarctic Cold Reversal (ACR) (Massaferro et al., 2009). An investigation carried out at Lake Mascardi (41°S) showed that chironomid assemblages (including *Phaenospectra*, *Podonominae*, *Parapsectrocladius* and some *Tanytarsini*) markedly changed during the Lateglacial–glacial transition and that chironomids most likely responded to climate cooling (Massaferro et al., 2010). While these existing South American chironomid records show great promise for determining the timing and magnitude of climate change, reconstructing paleotemperatures and identifying which species are actually indicative of cold temperatures is limited by the lack of a robust temperature inference model derived from modern chironomid distribution. If these changes in chironomid assemblages provide evidence of a climatic cooling around the time of the YD and ACR, they would allow direct comparisons with emerging climate records in the Southern Hemisphere (Dieffenbacher-Krall et al., 2007; Rees et al., 2008; Vandergoes et al., 2008; Woodward and Shulmeister, 2006, 2007).

In this study, a chironomid-based air temperature inference model for southern Patagonia from 46 to 54°S in Argentina and Chile is developed. Sixty-three lakes located along a W–E transect from the Andean sub-Antarctic forest to the arid Patagonian steppe sensitive to fluctuations in precipitation and temperature associated with changes in the westerly airflow (Markgraf et al., 2003) are sampled. These lakes are located in or close to past glacial ice limits and occur in the present sub-Antarctic forest and grass steppe vegetation zone, respectively, and should be sensitive to past fluctuations in tree line, precipitation and temperature being a key to obtaining a comprehensive climate model for southern Patagonia. The newly developed transfer function is then applied to the chironomid record of Lake Potrok Aike (PTA) to quantitatively reconstruct the change in mean annual temperature during the Lateglacial–glacial/Holocene transition. This reconstruction is compared with air temperature reconstructions obtained from chironomids, proxies and other archives from the Southern Hemisphere.

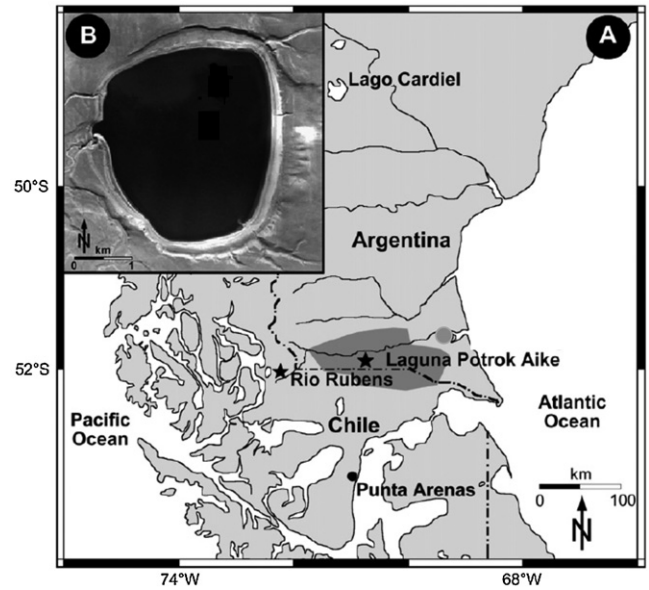

Fig. 1. Location map of Laguna Potrok Aike (star). A) Location in southern Patagonia, Argentina, B) aereal photograph of the lake. The figure was modified from Wille et al. (2007).

2. Study area

The climate and the vegetation of southern Patagonia are strongly influenced by the southern westerly winds (SWW). A strong precipitation gradient W–E is created by the influence of these winds, bringing heavy rainfall in the Chilean (west of the Andes) region developing a Patagonian and Magellanic rainforest and moorland. The Andes produce a major rain shadow effect leeward, and forced subsidence over the eastern side of the mountains bringing very dry conditions in Argentina's Patagonia and the presence of steppe and semi-desert conditions. In fact, mean annual precipitation decreases from ca. 1400 mm at the Chile/Argentina border to less than 200 mm on the eastern Patagonian plateau, where precipitation takes place mainly during winter bringing a negative hydrological balance oscillating between 300 and 500 mm per year (Fig. 1).

Winds, together with local topography, affect air temperature. Down-slope winds contribute to the drying of Argentina's Patagonia, characterized by a cold, windy steppe (Garreaud, 2009). The mean annual temperature in the area is 7.5 °C, with a mean of 0.6 °C in winter and 13.4 °C in summer, decreasing from the northeast to the southwest (Mancini, 2002; Tonello et al., 2009) (Fig. 1). In our training set, surface summer temperatures measured in February/March varied considerably from 6.2 °C to 27.5 °C.

The precipitation gradient shapes the vegetation of the area that vary from a deciduous forest at the western part of the Andes to a typical arid steppe ranging from associations of grasses to xerophytic forms, typical of the central part of Santa Cruz province. Further details about the vegetation of southern Patagonia are published elsewhere (Mancini, 2002).

3. Methods

3.1. Lakes for transfer function

Sixty-seven lakes were sampled from 1 to 1195 m a.s.l. and between 44–55°S and 66–73°W leading to a gradient of mean annual air temperature (MAT) of 6 °C (Table 1). Short cores were extracted from the deepest point of each lake using a

Table 1
Physical and chemical characteristics of the 63 lakes of the southern Patagonian training set.

Lake name	Longitude (°′)	Latitude (°′)	East/west of the Andes	Altitude (m a.s.l.)	Max. depth (m)	Secchi depth (m)	pH	Conductivity (μg/l)	Water T (°C)	MAT (°C)	MAP (mm)
Verde II	67.2	54.7	E	32	3.2	3.2	7.6	104.6	12.3	3.3	491.9
Blanco I	67.2	54.8	E	221	2.8	1.4	7.31	46.1	11.8	3.6	509.1
Margerita	67.2	54.8	E	120	14	4.3	8.05	150	12.3	3.6	508.7
Verde II	73.0	49.2	E	469	X	X	8.06	17	6.2	4.0	1389.0
Lolas II	73.0	49.2	E	452	3	X	7.00	43	6.7	4.3	1381.5
Lolas I	73.0	49.2	E	452	X	X	7.49	75	6.5	4.3	1379.9
Condor	72.9	49.2	E	588	8	X	6.59	29	14.5	4.4	1378.2
Torres	73.0	49.3	E	641	>20	X	7.10	15	9.7	4.5	1374.2
Doce	73.2	47.1	W	740	9.20	7.04	7	4	13.5	4.5	1889.4
Once	73.2	47.1	W	748	6.04	6.03504	7.01	2	15.4	4.5	1887.8
Huemul	72.9	49.1	E	622	>20	X	6.68	8	7	4.7	1371.5
Pinguinera Brown	67.5	55.0	E	5	4	0.9	8.51	114	13.3	4.8	571.4
Nothofagus	67.2	55.0	E	32	7	0.7	7.41	192	11.3	4.8	562.1
Condor	72.4	47.9	W	583	7.90	4.25	6.9	139	15	4.8	1114.2
Lavendera	66.9	55.0	E	34	3.2	1.35	8.32	242	10.6	4.8	553.0
Tres hermanos	72.5	46.8	W	266	11.9	1.5	8.17	309	17.6	4.9	1175.3
Moat	66.8	55.0	E	17	3.7	0.65	7.04	184.1	9.5	4.9	563.0
Diez	73.0	47.2	W	341	14.63	3.15	7.05	39	14.7	5.1	1779.7
Cofre	72.7	46.2	W	560	17.5	7	7.38	38.7	12.8	5.5	1567.4
Esmeralda	72.6	47.4	W	291	17	6.3	8.09	98	15.1	5.7	1355.8
Larga II	72.8	47.5	W	270	17.3	9.6	7.8	68.3	13.5	5.8	1595.9
Castor	71.8	45.7	W	690	8.5	8.5	7.99	88.7	12.2	5.9	791.2
Meche	72.5	47.2	W	980	14.00	10	7.7	108	8	5.9	1251.6
Norita	72.5	47.2	W	1070	X	7	7.5	100	9.5	5.9	1271.1
X667	71.9	45.8	W	718	9.5	3.3	7.82	72.5	12.9	6.0	807.8
Henley	72.4	47.1	W	700	14.30	4	7.3	157	10	6.1	1133.3
Seis	72.8	47.3	W	1103	8.50	6.71	7.14	8	7.1	6.1	1623.0
Compeanos	72.5	47.3	W	1070	X	3	7.7	30	11	6.1	1292.0
AlDabham	72.5	47.3	W	989	4.00	4	7.6	100	10	6.1	1265.0
Guanaco	72.4	47.1	W	440	7.15	4	8.58	496	14.8	6.1	1142.8
Erica	72.4	47.1	W	579	14.10	5.15	7.3	152	11	6.2	1174.4
Cinco	72.8	47.3	W	1195	1.25	1.24968	7.07	5	8.1	6.2	1603.2
Edita II	72.4	47.2	W	989	8.40	X	7.8	144	9	6.4	1213.9
Alta	71.9	50.4	E	537	0.4	X	7.74	2.78	7.7	6.4	261.4
Trece	72.8	47.2	W	414	17.16	7.02	7.01	54	16.7	6.4	1680.9
Cerda	72.1	45.1	W	274	16	7.1	7.23	31.4	12.8	6.4	1293.2
Cisnes	72.6	47.3	W	436	6	5.5	8.64	507	14.6	6.5	1414.3
Siete	72.7	47.3	W	1038	8.81	7.62	7.07	2	7.58	6.5	1585.1
Edita II	72.4	47.2	W	572	7.75	4.1	8.31	136.7	13.6	6.5	1211.5
Dos	72.8	47.2	W	383	15.24	5.05	7.248	46	13.42	6.6	1669.7
Envidia	72.0	46.2	W	463	5	1.5	7.89	224	13.4	6.6	782.7
Cuatro	72.8	47.3	W	963	4.11	4.1148	7.07	15	10.1	6.6	1610.1
Cerro frias I	72.8	50.3	E	588	X	X	7.78	390	13.5	6.6	945.8
Cerro frias II	72.8	50.3	E	559	X	X	6.70	240	27.5	6.6	941.4
Lobo	72.3	44.8	W	230	7	5.65	6.38	19.75	14	6.6	1574.0
Agustin	72.2	49.6	E	236	>20	X	8.21	512	20	6.7	541.1
Adelita	72.4	47.2	W	623	13.20	10.25	7.1	194	10.5	6.8	1150.1
Chela	72.4	47.2	W	608	29.40	8	7.4	290	8	6.8	1210.4
Huergo	72.1	51.7	E	157	4	X	X	43	7	6.9	326.4
Primero	72.8	51.0	W	290	9	1.3	9.04	1503	11.3	6.9	1314.5
Risaptron	72.5	44.4	W	142	17	6.1	7.22	32.2	13.5	7.0	1757.3
Ocho	72.7	47.2	W	728	27.43	7.01	7.07	21	8.2	7.0	1632.7
Tres	72.8	47.2	W	955	3.11	3.10896	7.82	46	9	7.0	1644.3
Ave	72.9	51.1	W	117	10.5	1	8.68	449	12.6	7.0	1493.6
Nueve	72.7	47.2	W	866	6.40	6.40	7.07	71	8.6	7.0	1616.0

Table 1 (*Continued*)

Lake name	Longitude (°′)	Latitude (°′)	East/west of the Andes	Altitude (m a.s.l.)	Max. depth (m)	Secchi depth (m)	pH	Conductivity (μg/l)	Water T (°C)	MAT (°C)	MAP (mm)
Foitzick	72.1	45.6	W	276	4.6	2.6	8.09	22	16.3	7.1	1115.6
Flores	72.8	51.2	W	116	19	2.2	8.52	457	12.1	7.6	1466.6
Mallin Anez	73.0	51.2	W	93	8.6	1.6	8.2	530	11.1	7.8	1607.3
Potrok Aike	69.2	51.6	E	16	100	X	8.37	2760	11.5	7.8	227.7
Lake 6	73.9	45.5	W	31	4.31	1.1	5.2	73	15.3	8.2	2362.7
Atraversado	72.2	45.8	W	368	10.5	3.3	7.78	71.3	14.3	8.4	1066.5
Lake 7	73.8	45.4	W	63	2.57	1.22	3.9	132	22.4	8.8	2394.0
Lake 5	74.1	45.5	W	48	7.66	3.32	6.4	61	16.8	8.8	2363.3
Lake 8	73.9	45.4	W	1	1.36	1.4	4.5	73	17.7	8.9	2393.7
Lake 1	74.1	45.3	W	6	5.8	3	5.775	108	23.7	8.9	2311.2
Lake 4	73.8	45.4	W	43	3.31	1.74	6.2	61	16.3	8.9	2411.3
Lake 3	74.1	45.4	W	18	1.61	1.29	6	61	20.8	9.1	2357.0

MAT, mean annual temperature; MAP, mean annual precipitation.

gravity corer. The first centimetre was used for chironomid analysis. Of the sampled lakes, 63 had data for all parameters thus were used for statistical analyses (see below). MAT, temperature of the warmest month (TWM) and mean annual precipitation (MAP) were obtained from the BRIDGE gridded data (http://clamp.ibcas.ac.cn/Clampset2.html) based on the New et al. (2002) data.

3.2. Potrok Aike and dating

Potrok Aike is a maar lake (51°58′S/70°23′W) located in the southernmost Argentinean Patagonian steppe (Fig. 1) in the Santa Cruz province where precipitation never exceeds 300 mm/year, in the Pali Aike volcanic field. This polymictic, mesotrophic to eutrophic lake has a maximum water depth of 100 m, a diameter of 3.47 km and its catchment area covers over 200 km^2. It is a closed basin with no permanent inflow or outflow, mainly fed by groundwater and episodic spring runoff after snowmelt. Detailed geological and vulcanological aspects are discussed in Zolitschka et al. (2006). Most of the Pali Aike volcanic field is composed by dry xeric type of the Magellanic steppe showing *Festuca gracillima* as dominant.

Sediment samples for this study were obtained from a composite profile obtained from two overlapping cores PTA 03/12 and PTA 03/13 and a short core for the top section, PTA 02/04. PTA 03/12 and 03/13 were obtained from the centre of the lake using an UWITEC piston corer system whereas the short core PTA 02/04 was recovered with an ETH gravity corer. These cores were obtained within the framework of the South Argentinian Lake Sediment Archives and Modelling project (SALSA) (http://www.salsa.uni-bremen.de). The stratigraphic correlation of the cores was facilitated by Ca data and photographs which resulted in a 1892-cm long composite stratigraphy that spans the last ca. 16,000 cal. years BP (Haberzettl et al., 2007). Detailed descriptions of the site settings, core lithologies, radiocarbon chronology, and paleoenvironmental evolution of the site are discussed in Haberzettl et al. (2007, 2008), Mayr et al. (2007, 2009), and Wille et al. (2007).

3.3. Chironomid analysis

Samples of 5–10 g sediment were prepared for chironomid analysis according to the methodology of Walker et al. (1991). Sediment was deflocculated using 10% KOH and sieved through 100 and 200 μm meshes. Material retained by the meshes was hand-sorted from a modified Bogorov counting tray under a dissecting microscope at 20×. Individual head capsules were placed on microscope slides in a drop of Hydro-Matrix®. Identification was made using a Nikon Phase microscope at 400× magnification. Head capsules were identified with reference to available taxonomic literature (Cranston, 2000; Wiederholm, 1983) and a Patagonian subfossil chironomid taxonomic identification guide (Massaferro et al., in press-a).

3.4. Statistical analyses and development of a transfer function

Conventional methods to develop a transfer function were applied (Birks, 1998). Percentages of taxa were used. Taxa with less than 2% in two lakes were deleted from the analysis to conform with other chironomid transfer functions (e.g., Walker et al., 1997; Larocque et al., 2001, 2006).

A detrended canonical analysis (DCA) with detrending by linear segments and non-linear re-scaling of axes was used to determine the modality (unimodal, linear) in the distribution of chironomid in the 63 studied lakes. Rare taxa were down-weighted for this analysis. If the lengths of the gradients were larger than 2, unimodal (Constrained Canonical Analysis, CCA) would be used. If the

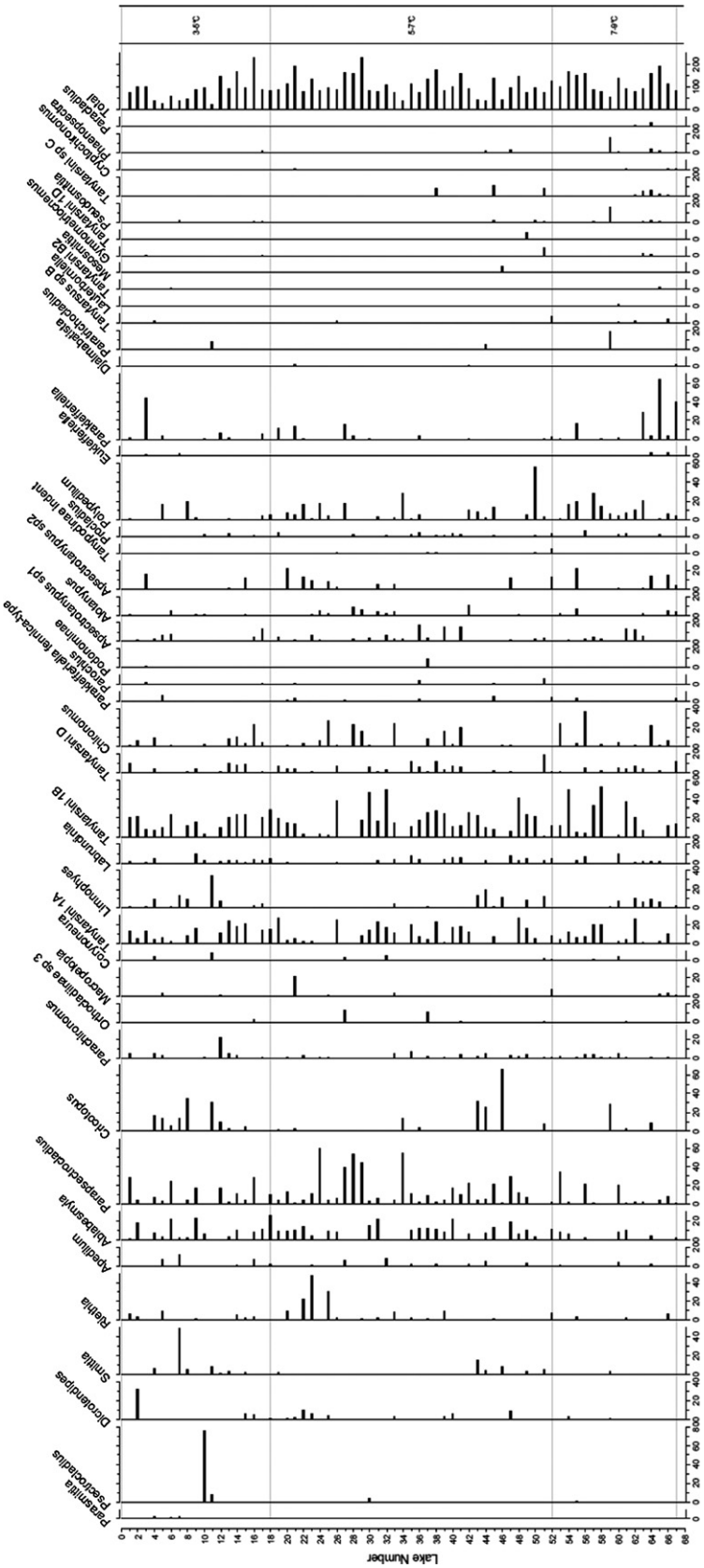

Fig. 2. Chironomid assemblages (in percentages) in the training set lakes. Total = total number of head capsules. The lakes have been ranked by their mean annual temperature (MAT) and zones were created artificially by MAT.

gradients were smaller than 2, linear (Redundancy Analysis, RDA) would be used (ter Braak and Šmilauer, 2002) to identify the parameters (using forward selection) influencing the distribution of chironomids in the 63 studied lakes. The program CANOCO (ter Braak and Šmilauer, 2002) was used for these analyses.

In case of unimodal distribution of the chironomids, Weighted-average-partial-least-squares (WA-PLS) would be used to develop the transfer function. Partial-least-square (PLS) would be used in the case of linear distribution (ter Braak and Šmilauer, 2002). The components to include in the model are chosen when the root-mean-square error of prediction (RMSEP) does not increase more than 5% by adding one more component (Birks, 1998).

To determine if the fossil samples in the Potrok Aike sediment were similar to the assemblages of the lakes included in the training set, a CCA (not shown) with fossil samples passively added to the training set lakes was used (Bigler et al., 2002). Samples located outside the 95% confidence interval would be considered as unfitted.

4. Results

4.1. Distribution of chironomids in the training set lakes

Fig. 2 shows the distribution of taxa in lakes ordered by MAT. The zones were artificially created to separate lakes between 3–5 °C, 5–7 °C and 7–9 °C. *Parasmittia* is the only "true" cold indicator as it was found only in lakes between 3 and 5 °C but in low abundances. *Psectroladius* had high percentages in lakes between 3 and 5 °C but was also found in one lake at 6 °C. *Dicrotendipes* and *Smittia* are more abundant in lakes between 3 and 5 °C but were also found in lakes until 7 °C. *Riethia* has its higher percentages in lakes at 5–5.5 °C but was present in many other lakes along the temperature gradient. *Cricotopus* seems to have a bimodal distribution with two peaks in lakes between 3 and 5 °C and in lakes between 6 and 7 °C. This bimodal distribution might be due to the fact that different species within the *Cricotopus* genus were not identified. *Parakiefferiella* also has a bimodal distribution, probably due to the undifferentiation between species. *Paracladius*, *Phaenopsectra*, *Cryptochironomus* and *Pseudosmittia* are mostly found in the warmer end of the temperature gradient.

4.2. Transfer function

The DCA of chironomid assemblages in the 63 lakes had lengths of gradient for three of the four axes larger than 2 (2.867, 1.880, 2.232, and 2.119) thus unimodal techniques should be used. A DCCA analysis identified Sechi depth, Conductivity, depth, MAT and water temperature as the five most important variables best explaining the variation in the chironomid assemblages. These five variables explained 41% of the variation in the chironomid assemblages. MAT explained alone 21% of the variance. Since MAT was available for all lakes, the transfer function was thus developed using all the 67 sampled lakes.

MAT produced the strongest transfer function as assessed by leave-one-out jacknifing. This transfer function, produced using WA-PLS with three components, had a coefficient of determination (r^2) of 0.64, a root-mean-square error (RMSE) of 0.83 and a maximum bias of 1.81 °C. Fig. 3 illustrates the relationship between predicted and measured temperatures. The residuals show no particular pattern in their distribution but suggest that cold temperatures are sytematically over-estimated.

4.3. Potrok Aike chironomids and MAT reconstruction

Only four taxa were found in the Potrok Aike lake sediment record for the past ca. 16,000 cal. years BP (Fig. 4). Until ca. 8500 cal. years BP, only three of the taxa were present: *Phaenopsectra*, *Cricotopus* and *Smittia*. *Polypedilum* appeared at ca. 8500 cal. years BP. In the newly developed transfer function, *Phaenopsectra* and *Polypedilum* are warm indicators with temperature optima estimated by WA-PLS at 22.2 °C and 12.7 °C, respectively. *Smittia* and *Cricotopus* have cold optima of 0.2 °C and 1.7 °C, respectively.

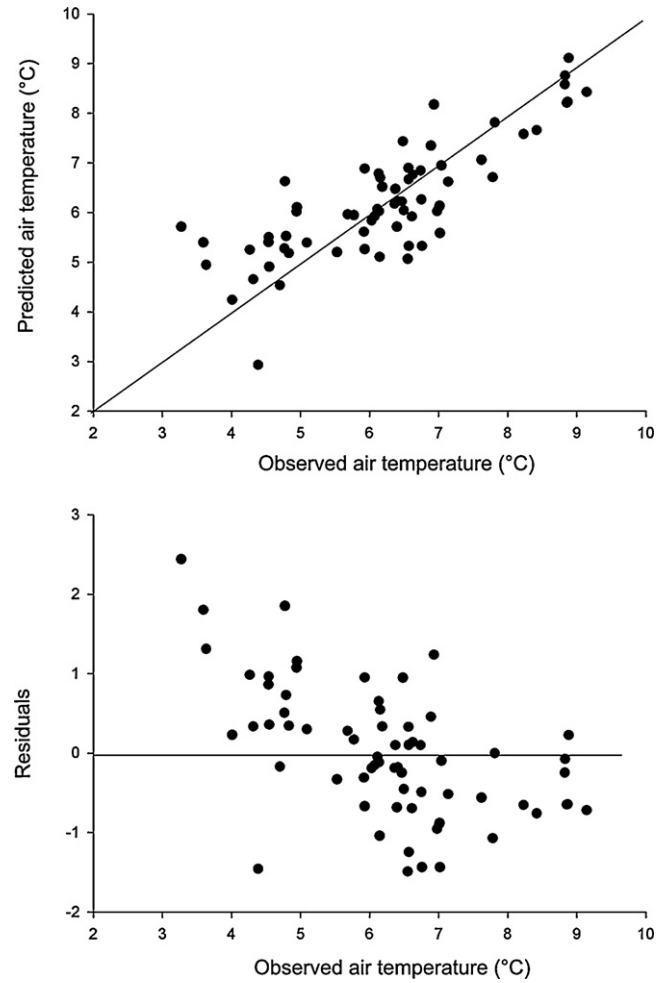

Fig. 3. Upper graph: Observed versus predicted air temperature. The line represents the 1:1 relationship. Lower graph: observed air temperature versus residuals.

The variation of these taxa through time lead to estimations of colder-than-the-record-mean (10.8 °C) temperatures (9.4 °C in average) between 16,000 and 10,400 cal. years BP, warmer-than-the-record-mean temperatures (12.2 °C in average) between 10,400 and 3500 cal. years BP and temperatures similar (10.5 °C in average) to the record mean from 3500 cal. years BP to the present (Fig. 4).

5. Discussion

5.1. Overview of the transfer function

As in many training sets developed in North America (Barley et al., 2006; Larocque et al., 2006; Porinchu et al., 2009; Walker et al., 1997), Scandinavia (Brooks and Birks, 2001; Larocque et al., 2001; Olander et al., 1999), Switzerland (Heiri et al., 2003) and Russia (Self et al., 2011), air temperature was one of the major factors influencing the 63 sampled lakes in Argentina. MAT explained more of the species variability (21%) than water temperature or TWM and the model created using WA-PLS had a highest r^2 and lower RMSE. While most of the other transfer functions cited above were

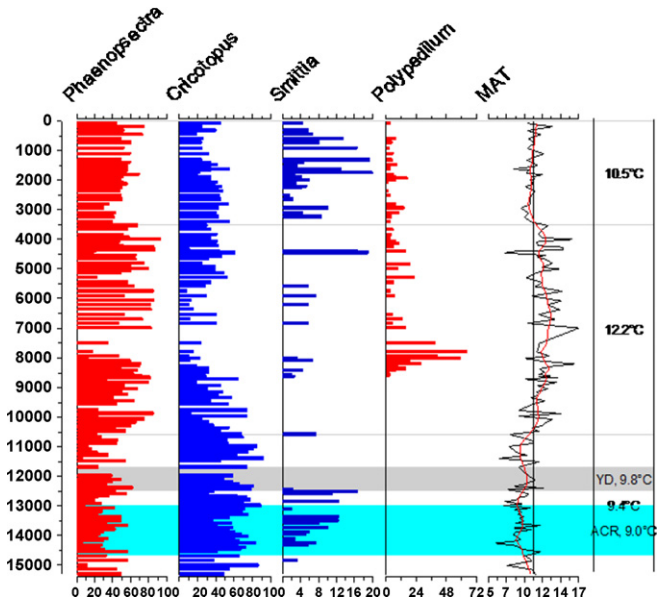

Fig. 4. Percentages of taxa at Potrok Aike and reconstructed mean annual temperature (MAT in °C). The percentages of taxa are presented. The zones were created using the ZONE program. In these zones, the average of MAT is written. The timing of the Younger Dryas (YD) and the ACR are identified in grey.

developed for water temperature or mean July (or August) air temperature, the temperature optima obtained here cannot directly be compared. However, warm (with temperature optima larger than 20 °C) indicators such as many *Tanytarsini*, *Phaenopsectra*, *Cryptochironomus*, *Polypedilum* and *Procladius* were also identified as warm indicators (Brooks et al., 2007). One divergence is with *Paracladius* which is found in cold episodes and cold lakes in the northern Hemisphere (Brooks et al., 2007) but one genus (*P. conversus*) is found in warmer environments in Australia (Cranston, 1982). Many of the cold (with temperature optima colder than 5 °C) indicators such as *Smittia*, *Cricotopus*, *Parakiefferiella*, *Corynoneura*, and *Podonominae* were also cold indicators in other training sets. However, as most taxa are considered at the genus level and could include very different species in both hemispheres, the comparison should not be an indication of the "validity" of the model but more as an interesting point of analogy as few chironomid studies are available from the Southern Hemisphere. In New Zealand, Woodward and Shulmeister (2006) also identified *Polypedilum* as a warm indicator, however most of their *Cricotopus* were found in warmer lakes. Dieffenbacher-Krall et al. (2007), found the highest proportions of *Chironomus* in lakes with mean summer temperature of less than 10 °C, with a steady decline in abundance in warmer lakes. In Tasmania, *Cricotopus* and *Polypedilum* were found mainly in cold lakes (Rees et al., 2008). These divergences are possibly due to different species being incorporated in these genus and not identified in the different training sets.

Although the transfer function is based only on 63 training set lakes and 44 taxa, the model statistics (r^2 = 0.64, RMSE = 0.83, and Max bias = 1.81 °C) are comparable to other transfer function of this size (revised in Brooks, 2006; Walker and Cwynar, 2006). To obtain larger r^2 and lower RMSEP, the gradient of MAT should be increased by sampling more lakes. This transfer function is a work in progress and, with time, we hope to be able to include more lakes and possibly increase the number of taxa and the model statistics (higher r^2, lower RMEP). However, at the moment, the reconstruction obtained at Potrok Aike suggests that the model already perform well, even when major changes in the lake levels occurred through the past and possibly affected the chironomid assemblages (Massaferro et al., in press-b). The four taxa found in the sediment of Potrok Aike are littoral (Brooks et al., 2007) thus might be more influenced by temperature than profundal taxa. Two are warm indicators (*Phaenopsectra* and *Polypedilum*) and two are cold indicators (*Smittia* and *Cricotopus*) although *Smittia* appears sporadically and can be more linked to erosion, as it is a semi-terrestrial taxon (Brooks et al., 2007).

5.2. Chironomids and air temperature

Chironomid assemblages are directly influenced by both air (e.g., during pupation, flight, reproduction, dispersal: Hofmann, 1986; Walker and Mathewes, 1989) and water temperature (e.g., via larval development, feeding, oxygen demand: Walker and Mathewes, 1989; Rossaro, 1991; Walker et al., 1991). In Potrok Aike, most taxa are littoral and are thus influenced by surface water, as well as air temperature. Olander et al. (1999) and Livingston and Lotter (1998) have shown a good correlation between air and surface water temperature in temperate lakes. The accuracy of chironomid-inferred air-temperature reconstruction at Potrok Aike is further exemplified by the small difference observed between the chironomid-inferred air temperature and the instrumental data (0.6 °C). In Lake Silvaplana, a deep (77 m) lake in Switzerland, similar results were obtained with assemblages composed of both littoral and profundal taxa, inferring mean July air temperatures for the past 100 years with high accuracy (0.7 °C) when compared with instrumental data (Larocque et al., 2009).

The difference between the inferences and the instrumental, although relatively small, could be due to other factors than temperature having an influence on the chironomid assemblages through time. Depth, conductivity and Secchi depth were factors identified in the training set as important. However, temperature (MAT and water) explained 30 of 41% of the variability in the chironomid assemblages. Amongst other factors, oxygen has been shown to be important to explain the distribution of chironomids (Quinlan et al., 1998) but since the assemblages at Potrok Aike consist only of littoral taxa, changes in oxygen are probably not important for chironomid variations.

5.3. Application of the transfer function to Potrok Aike

Potrok Aike is deeper than any of the training set lakes. This could have posed a problem if the chironomid assemblages found in Potrok Aike were not similar to those found in the training set lakes. This is not the case, as all samples of the Potrok Akike core added passively to CCA of the training set samples were within the 95% confidence interval. Furthermore, the application of the transfer function to lakes located outside the training set either to lakes located in another country (eastern Canada transfer function to lakes located in Switzerland and Italy), or lakes deeper than the training set lakes (Lake Silvaplana, 77 m) has been proven accurate by comparing the reconstructions obtained with ice core records (Larocque and Finsinger, 2008; Larocque-Tobler et al., 2010) or with instrumental data (Larocque, 2010). The results obtained have shown that the most important factor in reconstruction, is the resemblance of the assemblages to those of the training set samples, which was here also obtained.

5.4. Air temperature reconstruction and comparison with other paleoproxies

Up to day, the majority of the paloeproxy records from the southern Patagonian steppe are showing hydrological changes due to the position and the intensity of the westerlies. Indeed, the complexity of the atmospheric circulation patterns in the area is a very strong climate forcing that may blur other climate signals such as temperature. Changes in wind intensity are documented

in the sediment record of PTA since 8600 cal. years BP where increasing pollen input from the Andean forest, higher total inorganic carbon (TIC) and low Ti sediment concentrations suggest stronger west winds during the early Holocene that persists until today (Haberzettl et al., 2007; Mayr et al., 2007; Wille et al., 2007). Later on, Anselmetti et al. (2009) based on seismic evidence from this lake, also found an intensification of the westerlies at ca 6000 cal. years BP. Although the chironomid assemblages at PTA seem to have been influenced by precipitation (lake level changes) (Massaferro et al., in press-a), it was hypothesized that these changes could also reflect temperature changes, as MAT instead of precipitation, was identified as one of the most important factors explaining the distribution of chironomids (this study). In the context of the PASADO project (http://www.pasado.uni-bremen.de), chironomids could be the only proxy being able to provide a temperature reconstruction which could be compared with precipitation and lake level reconstructions obtained by pollen and other proxies.

The coldest temperatures (9.0 °C in average) were reconstructed by chironomids at PTA during the period between ca. 16,000 and 10,400 cal. years BP, the warmest temperatures (12.2 °C in average) between 10,400 and 3500 cal. years BP and average temperature of 10.5 °C were inferred between ca. 3500 cal. years BP and today. Today's MAT is 7.8 °C (as calculated with the New et al., 2002 data) while the chironomid-inferred MAT from the surface sample is 8.4 °C, suggesting a bias of 0.6 °C which is below the RMSE of the model (0.83 °C) and in line with differences between instrumental data and chironomid-inferred temperatures at various sites in the Northern Hemisphere (Larocque and Hall, 2003; Larocque et al., 2009; Larocque-Tobler et al., 2011). This result brings some confidence in the accuracy of the chironomid-inferred MAT at PTA, although we must assume that this accuracy remained for the past 16,000 cal. years BP.

During the Lateglacial–glacial, the chironomid-inferred temperatures at PTA compares well with the temperature reconstructed in the Antarctic ice core with slightly warmer temperature at 15,000 cal. years BP, decreasing during the Lateglacial–glacial with the coldest temperatures recorded during the ACR and a subsequent increase to the YD (Pedro et al., 2011). In New Zealand, glacier fluctuations during the ACR suggested a decrease in temperature of 3–4 °C (Anderson and Mackintosh, 2006) which is similar to the amplitude reconstructed by chironomids at PTA Pollen and chironomid temperature reconstructions showed a cold ACR but a YD similar to the previous (15,000–14,000 cal. years BP) and following (11,000–10,000 cal. years BP) periods (Vandergoes et al., 2008). In Tasmania, the chironomids did not inferred cold climate during the ACR but the colder period was evident with loss-on-ignition (LOI) (Rees and Cwynar, 2010). Terrestrial proxies showed no evidence for a Younger Dryas cooling event in or around New Zealand, but there were signs of the Antarctic Cold Reversal in and around New Zealand and off southern Australia (Williams et al., 2009). During the Holocene, the chironomid-inferred temperatures at PTA were higher than average between 8000 and 3500 cal. years BP with a slow decreasing trend. This pattern was similarly recorded by Alkenone from a Chilean continental core (Lamy et al., 2002), a $\delta^{13}C$ profile from Lago Fagnano (Moy et al., 2011), the Taylor Dome δD record (Steig et al., 2000) and in the Huacaran (Peru) ice-cap $\delta^{18}O$ record (Thompson et al., 1995). Very few other quantitative temperature reconstructions exist from the Southern Hemisphere to compare with.

The use of chironomids for quantitative reconstruction of temperature has recently been developed in New Zealand (Woodward and Shulmeister, 2006; Dieffenbacher-Krall et al., 2007), or Tasmania (Rees et al., 2008). At present, the lack of chironomid temperature inference models from South America is a serious impediment in providing robust, quantifiable estimates of temperature from existing Lateglacial–glacial and Holocene chironomid records. Progress in this area is underway and Massaferro et al. (2010) presented the results of a northern Patagonian chironomid-temperature inference model derived from a modern training set of 32 lakes. The model has an r^2 of 0.47 and a RMSEP of how 1.74 °C. The inference model covers an altitudinal range of 70–2000 m and a mean annual air temperature range of 4–12 °C.

5.5. Precipitation reconstructions in southern Patagonia

Other quantitative reconstructions performed in this extreme of Patagonia are based on pollen analysis and reconstruct precipitation. Tonello et al. (2009) performed the first pollen based quantitative precipitation reconstruction using a calibration dataset of 112 soil samples and 59 pollen types collected in southern Argentinean Patagonia. The authors developed a WA-PLS model which was applied to fossil samples from Lake Cerro Frias (GPS) located in an ecotonal forest-steppe area. Reconstructed precipitation values showed dry conditions during the Pleistocene–Holocene transition. Their results also indicated a southward shift of the westerlies during the early Holocene. More recently, Schabitz et al. (in press) presented the first quantitative pollen reconstruction for the arid Patagonian steppe. The authors developed a WA-PLS model using 101 soil samples from the Patagonian steppe. The model was tested in 16,000 cal. years BP core from PTA. The results indicated that precipitation was lower during the Lateglacial/glacial, increased towards the Holocene and remained on a higher level than during the Lateglacial glacial. These general patterns corresponded well to the temperature reconstruction with chironomids (this study) and in Antarctica (Pedro et al., 2011) with drier and colder climate during the Lateglacial–glacial. During the Holocene, the pollen reconstruction (Schabitz et al., in press) and the Ca content in the sediment of PTA (Haberzettl et al., 2009) suggested dry periods between 8700–7200 cal. years BP and 4600 and 3800 cal. years BP. During these periods, the chironomid temperatures were the warmest inferred. Schabitz et al. (in press) suggest that during the Lateglacial–glacial, precipitation was linked with temperature while during Holocene times the wind influences over the southern South American continent was the force driving the precipitation.

6. Conclusions

The 63-lake transfer function indicated that mean annual temperature (MAT) is one of the most important factors explaining the distribution of chironomids and a transfer function was built using WA-PLS. The statistics of the model (r^2 = 0.64, RMSE = 0.83 and Max bias = 1.81 °C) are comparable to other training sets however, they could possibly be improved by adding more lakes in a wider temperature gradient.

Using this transfer function, the chironomids at PTA inferred colder-than-average temperatures during the Lateglacial–glacial and the coldest inferences during the ACR. The chironomid-inferred temperatures were warmer-than-the-average between ca. 8000 and 3000 cal. years BP with a decreasing trend. The general pattern of temperature changes was similar to those reconstructed in various parts of the Southern Hemisphere from terrestrial and marine records. Very few quantitative records are available for comparisons but chironomid transfer functions are being developed and applied in various part of the Southern Hemisphere.

During the Lateglacial, the temperature and precipitation records were linked: cold temperatures were associated with low precipitation levels. This relationship changes during the Holocene when two of the warmest periods were associated with low

precipitation levels. This could be due to an increase in wind direction and strengths which became the factors driving precipitation.

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