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A multiproxy reconstruction of effective precipitation in the central Austrian Alps since the Little Ice Age

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ABSTRACT: Lake levels can act as valuable proxy sources for long-term effective precipitation dynamics. In this study, lake-level fluctuations were reconstructed from the Little Ice Age (LIA) until the present using a multiproxy paleolimnological approach from Lake Moaralm (Moaralmsee) in the Niedere Tauern Alps, Austria. Quantitative lake level reconstruction techniques were applied to the sediment core data using intralake (Moaralmsee) calibration models based on fossil Chironomidae and Cladocera assemblages, and supplementary models based on oribatid mites and loss-on-ignition were used. The results showed that the inferred lake-level trends were strongly correlated among one another and also with the observed precipitation record from an adjacent weather station since 1860 AD. Periods of low lake level were reconstructed for ca. 1600–1650 AD and 1700–1900 AD, while high lake level periods occurred from ca. 1650–1700 AD and from ca. 1900 AD to the present. These results were in good agreement with previous records on lake level and precipitation patterns in the European Alps, though with some spatiotemporal differences. Our records of long-term patterns of effective moisture, combined with the previously established temperature variability since the 17th century, suggested that a period of high effective moisture occurred between ca. 1650 and 1700 AD during the LIA, after which moisture levels decreased. High temperatures during the last century were accompanied by increasing moisture, and the lake levels are now at a 400-yr maximum. This study provides a new proxy for spatiotemporal moisture patterns that is invaluable for improved understanding of synoptic climate variability for periods prior to the observational records.

KEY WORDS: Chironomidae · Cladocera · Lake sediments · Loss-on-ignition · Oribatida · Paleoclimate · Precipitation

1. INTRODUCTION

Due to the present day global warming, increased interest has been directed towards long-term patterns in climate variability (Jones et al. 2009) in response to the need for knowledge about the effects and magnitude of the ongoing changes. Unfortunately, instrumental records do not extend far into the past, and those that do are scarce and often very fragmentary (Vesajoki & Holopainen 1998, Etien et al. 2009). Therefore, spatiotemporal patterns cannot be satisfactorily resolved from these data. Paleoclimatic archives, such as those stored in lake sediments, can be used to compensate for this lack of information about past climates. However, paleoclimatic reconstructions have various problems associated with modeling uncertainties and the proxies used always come with some error (Mann et al. 1999,

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Goosse et al. 2005). Therefore, it is extremely important to assess these reconstructions using multiple proxies and spatially comprehensive data. There is also a great need for data on long-term precipitation trends (Barley et al. 2006, Luoto & Sarmaja-Korjonen 2011, Magny et al. 2011a, Nevalainen et al. 2011a), as the focus until now has been strongly on temperature reconstructions (Jones et al. 2009). Changes in lake levels of enclosed basins reflect effective precipitation patterns or moisture patterns, i.e. the relationship between precipitation and evaporation (Mason et al. 1994, Vassiljev 1998). Lake sediment research, including studies on sediment composition and biotic sedimentary assemblages, has long been used to examine long-term lake-level and effective moisture fluctuations (Harrison & Digerfeldt 1993, Hofmann 1998).

Hydrological changes originating in the atmosphere are strongly reflected in lithostratigraphical properties of lake sediments, and therefore physical characters of sediments can be used in paleohydrological reconstructions. For example, the organic content of lake sediments is dependent on water depth (Håkanson 1977) that makes loss-on-ignition (LOI) analysis (Dean 1974, Heiri et al. 2001) a sensitive proxy for lake-level changes (Laird & Cumming 2008, Magny et al. 2011b). Although the proportion of organic matter is related to climate at larger scales (Korhola et al. 2002) and to nutrient input at the catchment scale (Luoto & Nevalainen 2011), the within-lake variability in organic content is mostly dictated by water depth, with the highest organic proportions found in the deep water samples (Shuman 2003, Luoto 2010, Nevalainen et al. 2013).

Midges (Diptera: Nematocera) and Cladocera (Crustacea) have been shown to have a statistical correlation with water depth at a regional scale (Korhola et al. 2000) and also, using surface sediment fossil assemblages, at the scale of a single site (Kattel et al. 2007, Luoto 2010, Engels & Cwynar 2011, Nevalainen 2011, Zhang et al. 2012). The relationship between aquatic invertebrates and water depth is mostly indirect and mediated through other limnological factors, such as oxygen availability, temperature, substrate, and submerged vegetation. Nevertheless, this relationship provides the opportunity to construct intralake training sets (i.e. calibration sets) and associated transfer functions for long-term lake-level reconstructions from sediment downcores (Engels et al. 2012, Nevalainen & Luoto 2012). It should be noted that the use of an intralake training set is usually strictly valid only in a downcore from the training set lake itself (Velle et al. 2012); however, it has also been shown that intralake models may provide good reconstructions of observed data when applied to non-focal sites too (Nevalainen & Luoto 2012).

Midges (mostly Chironomidae) are known to be strongly influenced by the surrounding air and water temperature, in addition to water depth (Brooks 2006), and this has also been shown for the Cladocera (Luoto et al. 2011) and their fossil ephippia (Kultti et al. 2011, Nevalainen et al. 2012). The complex relationship between the signals of water depth and temperature in midge- and Cladocera-based reconstructions can be assessed, for example, by examining the core taxa for their environmental associations in the training set (indicator taxa) and by examining the reconstructions against their scores along the primary ordination axis in an ordination analysis. The primary environmental forcing factor appears to be lake-specific (Luoto 2009).

A third invertebrate group that has potential in lake-level reconstructions is oribatid mites (Acarina: Oribatida). The fossil oribatid assemblages are mostly a mixture of limnic, limno-telmatic (i.e. lake edge), and terrestrial species (Solhøy 2001), and their intralake distribution is restricted to shallow littoral areas (Luoto 2012). However, because they are absent from deep water sites, the use of oribatids in lake-level reconstructions is probably limited to shallow lakes, and furthermore they can only give indications for lake-level lowering (increasing abundance) when the downcore samples are taken from the deepest points of lake basins.

In the current study, we used lake sediment archives of fossil invertebrate communities and physical properties of the sediment to reconstruct past water level fluctuations from a climatically ultra-sensitive lake (Thompson et al. 2005): Lake Moaralm (Moaralmsee) in the Niedere Tauern Alps, Austria. Quantitative lake-level reconstruction models using intralake (Moaralmsee) calibration models based on midge and Cladocera assemblages (Luoto 2012, Nevalainen 2012) were applied to a previously published fossil record (Luoto & Nevalainen 2012). In addition, we developed and applied polynomial/linear models based on intralake oribatid mite remains and LOI patterns for further evidence of lake-level changes. We aimed to show that fossil invertebrates, although rarely used, are a powerful tool in reconstructing past lake-level dynamics. The present results can be used as valuable evidence of local and regional effective precipitation patterns during the past centuries, and as a point source for assessment of global changes.

2. REGIONAL SETTING

Moaralmsee (47° 37′ N, 13° 80′ E) is located in the Niedere (Schladminger) Tauern Alps in Austria (Fig. 1). The Niedere Tauern forms a compact but imposing massif of crystalline and limestone bedrock. Moaralmsee is separated from the corrie backwall to its south by an upper basin and a moraine field, making the basin mostly groundwater fed. The lake lies at an altitude of 1825 m a.s.l. and above the present treeline. Grassy parts of the catchment are active cattle pastures, but the lake has remained ultraoligotrophic (mean total phosphorus 2009 to 2012 was 3.7 µg l^{-1}). The maximum length of the lake is 232 m, maximum width 127 m, and maximum depth 6.1 m. The water temperature in Lake Moaralmsee is unusually cold compared to other lakes at similar altitude in the region due to slower snowmelt, and thus has been judged to be ultra-sensitive to temperature changes (Thompson et al. 2005, Luoto & Nevalainen 2012). The lake was chosen for study because it was considered to be in a close to pristine state and to have a homogeneous inlake habitat distribution (lacking, for example, dense littoral vegetation or inlets). The lack of inlets makes the lake very suitable for lake-level and effective moisture studies (Mason et al. 1994). The outlet located on the lower corrie rim determines the maximum lake level. The water supply of the lake is all atmospheric in origin, including direct rainfall, groundwater and snowmelt input, and is thus indicative of effective precipitation.

3. MATERIALS AND METHODS

3.1. Sediment material and analyses

The chironomid, oribatid, and Cladocera assemblages in the surface sediment sample dataset and in the sediment core from Moaralmsee are previously published (Luoto 2012, Luoto & Nevalainen 2012, Nevalainen 2012). The sediment sampling was performed using a Kajak gravity corer in autumn 2010. The chironomid-based water depth calibration model is presented by Luoto (2012), whereas the Cladocera-based water depth calibration model was developed in this study. The chironomid-based model is based on 30 intralake samples along the depth gradient (measured water depth at the sampling sites) in Moaralmsee, whereas the Cladocera-based model is based only on 20 samples due to the limited presence of their fossil remains (Fig. 1b). The chronology of the Moaralmsee core is based on ^{210}Pb dates (constant rate of unsupported ^{210}Pb supply [CRS] model) and on the age-depth model applied by Luoto & Nevalainen (2012). It should be noted that ages over ~200 yr should be interpreted cautiously due to the dating method and possible variability in the sedimentation rate in the lower part of the core. LOI was performed from fresh sediment using a sample weight of approximately 10 g. The samples were dried at 105°C for 12 h and ignited in an oven at 550°C for 2 h (Dean 1974, Heiri et al. 2001). The LOI was not analyzed from the topmost core sample as these contained too little material to be analyzed.

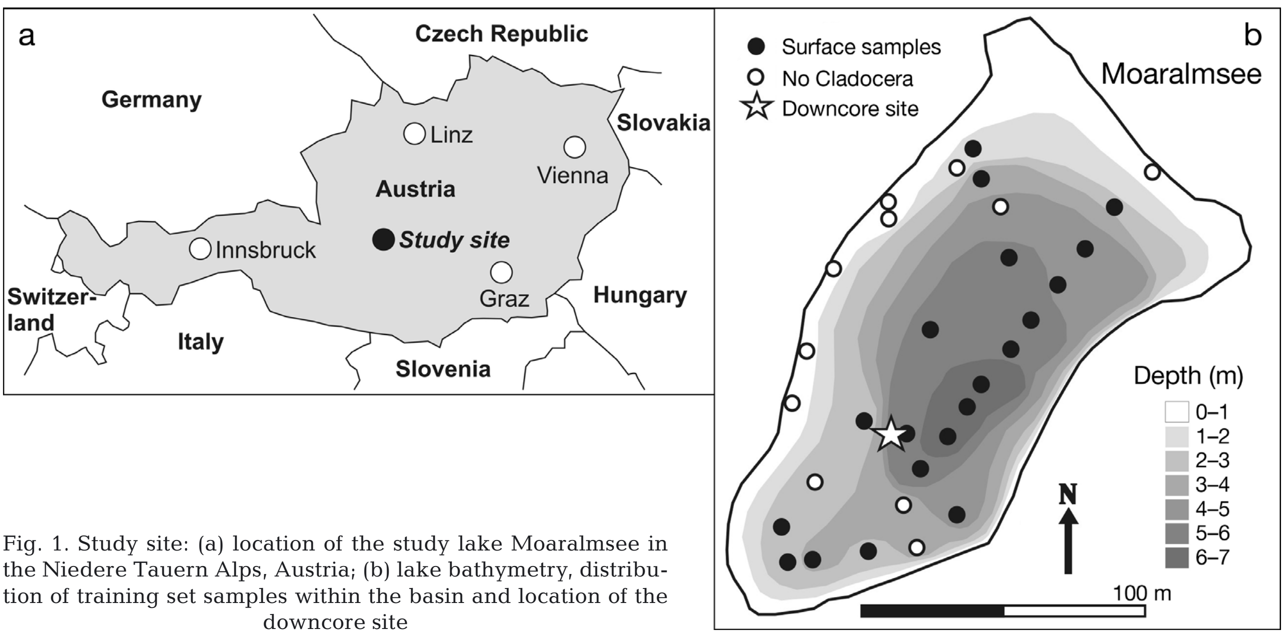

Fig. 1. Study site: (a) location of the study lake Moaralmsee in the Niedere Tauern Alps, Austria; (b) lake bathymetry, distribution of training set samples within the basin and location of the downcore site

3.2. Numerical analyses

All data analyses were performed using relative taxon abundances without any taxa deletions. In the development of Cladocera-based water depth inference model, several calibration techniques were used to select the method that perform best by giving a high squared correlation between jackknife-predicted and observed values (r^2_{jack}), a low root mean squared error of prediction (RMSEP), and low mean and maximum biases in jackknife residuals. The methods used were simple weighted averaging (WA) with an inverse deshrinking regression, WA with taxon tolerance weighting (WA_{tol}) and an inverse deshrinking regression, simple WA with a classical deshrinking regression, WA with WA_{tol} and a classical deshrinking regression, partial least squares (PLS), and WA-PLS (Juggins 2007). The inference models were developed and tested with the program C2 (Juggins 2007). The development of the chironomid-based water depth reconstruction model is described by Luoto (2012).

Because intralake training sets can be sensitive to spatial autocorrelation (Engels et al. 2012, Luoto 2012, Velle et al. 2012), i.e. the tendency of closely located sites to resemble one another (Legendre 1993), a Mantel non-parametric test (Mantel 1967, Mantel & Valand 1970) was used for spatial analysis of the Cladocera data. Mantel test results for the chironomid data are given in Luoto (2012). The Mantel test is a permutation test for correlation between 2 distance or similarity matrices. It has been shown that the Mantel correlogram successfully detects spatial correlation in ecological data (Borcard & Legendre 2012). A Bray-Curtis distance was used for the biological distance matrix and geographical distance between the sites for the spatial distance matrix using 1000 randomizations.

Linear and polynomial regression were used as novel ways of reconstructing lake levels based on LOI in the surface sediments of Moaralmsee and intralake distribution of oribatid mite remains, respectively. Normality of the data was assessed using Kolmogorov-Smirnov and Shapiro-Wilk significances. The intralake distribution of oribatids and patterns in LOI are described in Luoto (2012), whereas the models were constructed in this study. Two samples from the limnotelmatic contact were excluded from the LOI analysis because they consisted mostly of plant material.

Principal component analysis (PCA) was used to investigate patterns in chironomid and Cladocera assemblages in the downcore data. PCA was chosen due to the linear nature of the species data, and the results are previously published by Luoto & Nevalainen (2012). The statistical significance of the chironomid- and Cladocera-based water depth reconstructions were tested using the random transfer function (TF) method (Telford & Birks 2011). This method was used to determine whether the present reconstructions explained a larger proportion of the variance in fossil data than most of 999 reconstructions of random environmental data. Statistical significance test calculations were performed using the R statistical software (R Development Core Team 2011) package palaeoSig (Telford 2013). The Pearson product-moment correlation coefficient (*r*) and the level of statistical significance (significance level $p \leq 0.05$) were used to test the relationships between the different proxies. In addition, the reconstruction results, including a combined reconstruction (mean of the proxy inferences), were tested for correlations against the instrumentally measured annual precipitation record (1860–2010) from a closely located weather station in Bad Ischl (47° 71′ N, 13° 65′ E) using 20 yr running means in the observational record. Thus, the reconstructions were correlated with the instrumental trends (low frequency) not wiggles (high frequency). All correlations were calculated from raw data. The proxy time-series were tested for temporal autocorrelation using the autocorrelation function in the program PASW Statistics 18 (Norusis 2010) to assure reliable correlation calculations.

4. RESULTS

The performance statistics of the chironomid-based lake level calibration model (Luoto 2012) are described in Table 1 and the 1:1 relationships between

Table 1. Chironomid- and Cladocera-based inference models of water depth and the training set characteristics from Lake Moaralm (Moaralmsee) in the Niedere Tauern Alps, Austria. $WA_{tol\_classical}$: weighted averaging with taxon tolerance weighting and a classical deshrinking regression; $PLS_{comp.1}$: partial least squares with 1 regression calibration component; r^2_{jack}: squared correlation between jackknife-predicted and observed values; RMSEP: root mean squared error of prediction

	Chironomid-based inference model	Cladocera-based inference model
Number of samples	30	20
Gradient (m)	0.1–6.1	1.8–6.1
Calibration technique	$WA_{tol\_classical}$	$PLS_{comp.1}$
r^2_{jack}	0.905	0.628
RMSEP (m)	0.621	0.904
Mean bias (m)	–0.137	–0.001
Maximum bias (m)	0.876	2.034

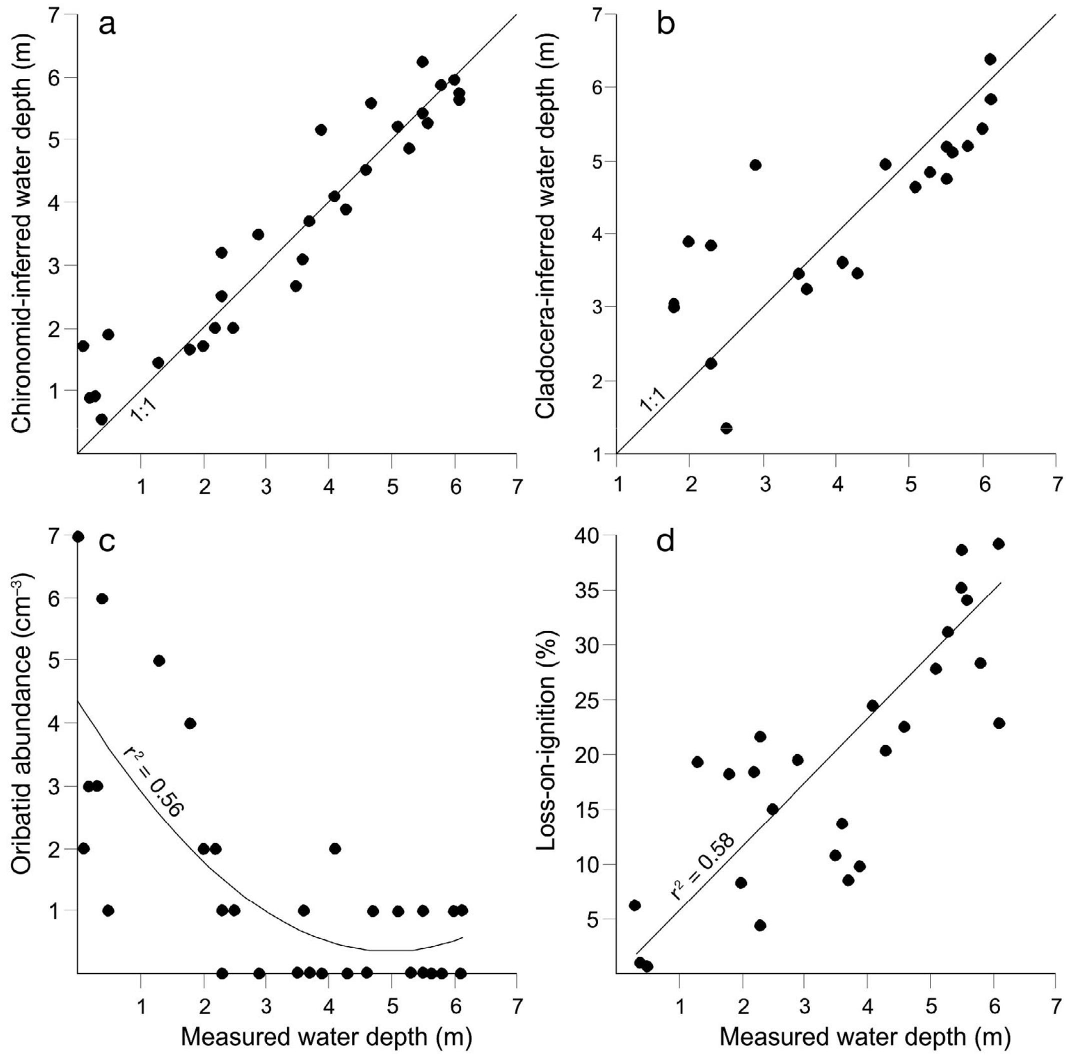

Fig. 2. Reconstruction models. Relationship (1:1) between observed and inferred water depth in the intralake training sets of (a) chironomids (Luoto 2012) and (b) Cladocera from Moaralmsee in the Niedere Tauern Alps, Austria. The chironomid-based model uses weighted averaging (WA) and the Cladocera-based model uses the partial least squares (PLS) technique (see Table 1 for details). (c) A second order polynomial function between volumetric oribatid abundances and water depth and (d) a linear relationship between loss-on-ignition (LOI) and water depth in the surface sediment dataset from Moaralmsee

observed lake levels and those inferred from chironomid data are shown in Fig. 2a. The fossil Cladocera assemblages along the water depth gradient in Moaralmsee showed strong habitat-specificity (Nevalainen 2012) that justified the development of a calibration model for water depth. Of the 31 surface sediment samples, 20 contained enough (>70 individuals) Cladocera remains to be included in the model. The best of the model types tested, providing the highest r^2_{jack} and lowest RMSEP and mean and maximum biases (Table 1), used PLS technique with 1 regression calibration component. The Cladocera-inferred water depth within the model showed strong correlation ($r = 0.85$) with measured water depth, although the values were mostly overestimated at depths <3 m (Fig. 2b). The Mantel test on the Cladocera assemblages indicated that there was no significant spatial autocorrelation in the data ($r = 0.14$, $p = 0.094$). Autocorrelation results of the chironomid data and its consequences are discussed in detail by Luoto (2012); although there was some slight spatial autocorrelation in the dataset, it was not ecologically meaningful.

The second order polynomial regression for water depth based on oribatids had a Spearman's r_s of 0.66 and coefficient of determination (r^2) of 0.56 (Fig. 2c), whereas the linear regression model for LOI had a Pearson's r of 0.76 and r^2 of 0.58 (Fig. 2d). Both models were significant at $p \leq 0.001$.

The chironomid-inferred water depth varied between 3.7 and 5.9 m and the Cladocera-inferred water depth between 2.3 and 5.1 m (Fig. 3a,b). The sample-specific errors of estimation (eSEPs) varied in the chironomid-based reconstruction from 0.7 to 1.1 m and in the Cladocera-based reconstructions from 1.0 to 1.2 m. There were no particular trends in the eSEPs along the stratigraphies (Fig. 3a,b). In both reconstructions, the minimum inferred lake depth was at 7 cm and maximum depth at 1 cm in the stratigraphy. In general, the chironomid-inferred values (mean depth 5.3 m) were higher than those inferred using Cladocera (3.9 m). The oribatid mite-inferred water depth varied between 1.8 (at 14 cm) and >4.0 m (at 21–18, 9, and 6–0 cm), whereas the LOI-inferred water depth varied between 2.6 (LOI = 14.8% at 22 cm) and 5.5 m (LOI = 32.6% at 1 cm) (Fig. 3c,d). Considering all the lake level proxies, relatively low lake levels were inferred between 24 and 22 cm (~1600 AD), higher lake levels between 21 and 18 cm (~1700 AD), lowered lake levels between 17 and 7 cm (18th and 19th centuries), and elevated lake levels from 6 cm (~1900 AD) until the present (Fig. 3). The modern measured water depth at the sampling site was 5.5 m, whereas the chironomid-inferred water depth for the surface sample was 5.4 m and the Cladocera-inferred water depth was 5.1 m, both within the models' RMSEPs and the sample-specific eSEPs. Moreover the oribatid-inferred value of >4 m (a depth of 4.0 to 6.1 m was inferred from the absence of oribatids) roughly corresponded to the measured water depth. LOI was not measured from the surface sediment sample, but the inferred water depth at 1 cm (5.5 m) was similar to the modern measured value.

All chironomid samples had enough head capsules for reliable analysis, but the samples at 15, 14, and 7 cm contained <70 Cladocera individuals (Fig. 4). With both proxies, all the downcore samples had >95% coverage of fossil taxa present in the calibration set and >50% of water depth indicator taxa, i.e. those having a statistically significant relationship with water depth (assessed using generalized linear modeling and generalized additive modeling in Luoto 2012 and Nevalainen 2012, respectively). The results of the reconstruction significance tests (random TF) showed that the chironomid-based water depth reconstruction ($p = 0.04$) was statistically significant, whereas the cladocera-based reconstruction ($p > 0.05$) failed the test. The chironomid PCA Axis 1 showed clear correlation and the Cladocera PCA Axis 1 extremely strong correlation with the

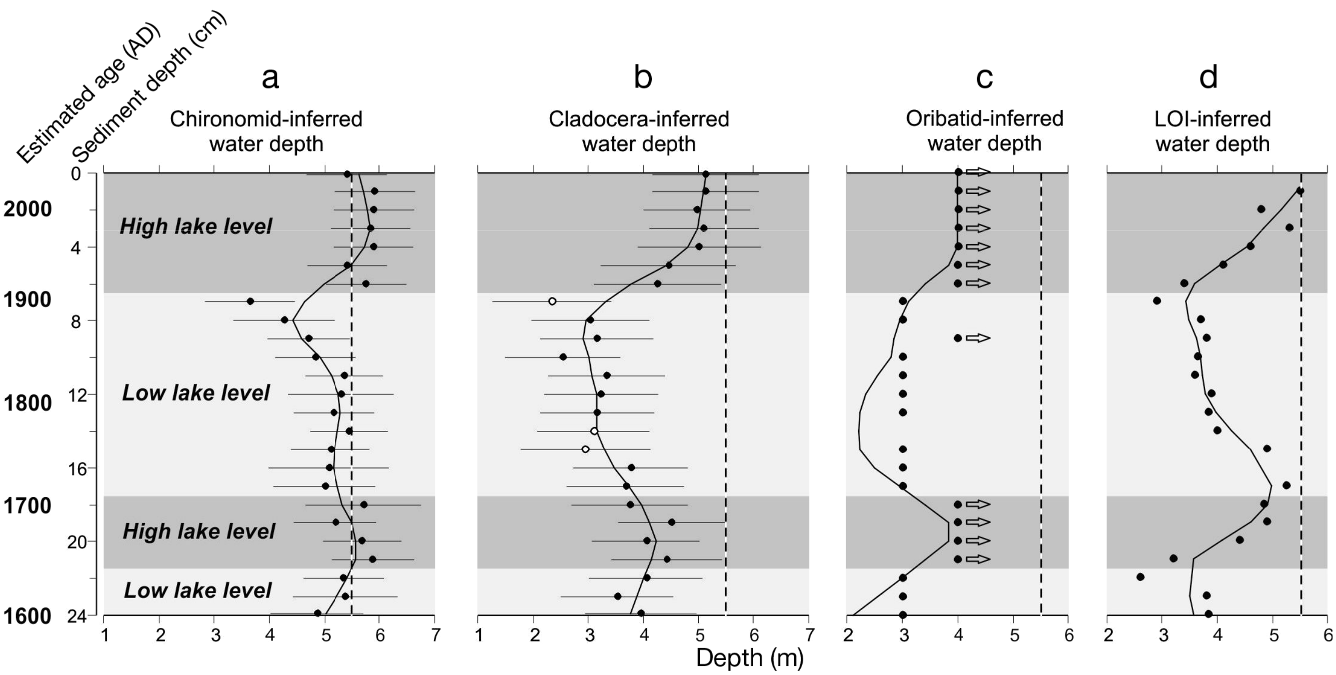

Fig. 3. Reconstructions. (a) Chironomid-, (b) Cladocera-, (c) oribatid-, and (d) loss-on-ignition (LOI)-inferred water depths in the sediment profile from Moaralmsee in the Niedere Tauern Alps, Austria. The vertical dashed lines represent the modern measured water depth at the sampling site, the horizontal error bars represent the sample-specific errors of estimation (eSEPs), and the results are run through a locally weighted scatterplot smoothing (LOWESS, span 0.3). The open circles in the Cladocera-based reconstruction represent samples with low counting sums. The oribatid-based polynomial regression model can reconstruct water depths only up to 4 m; the arrows indicate that the actual water depths may have been higher

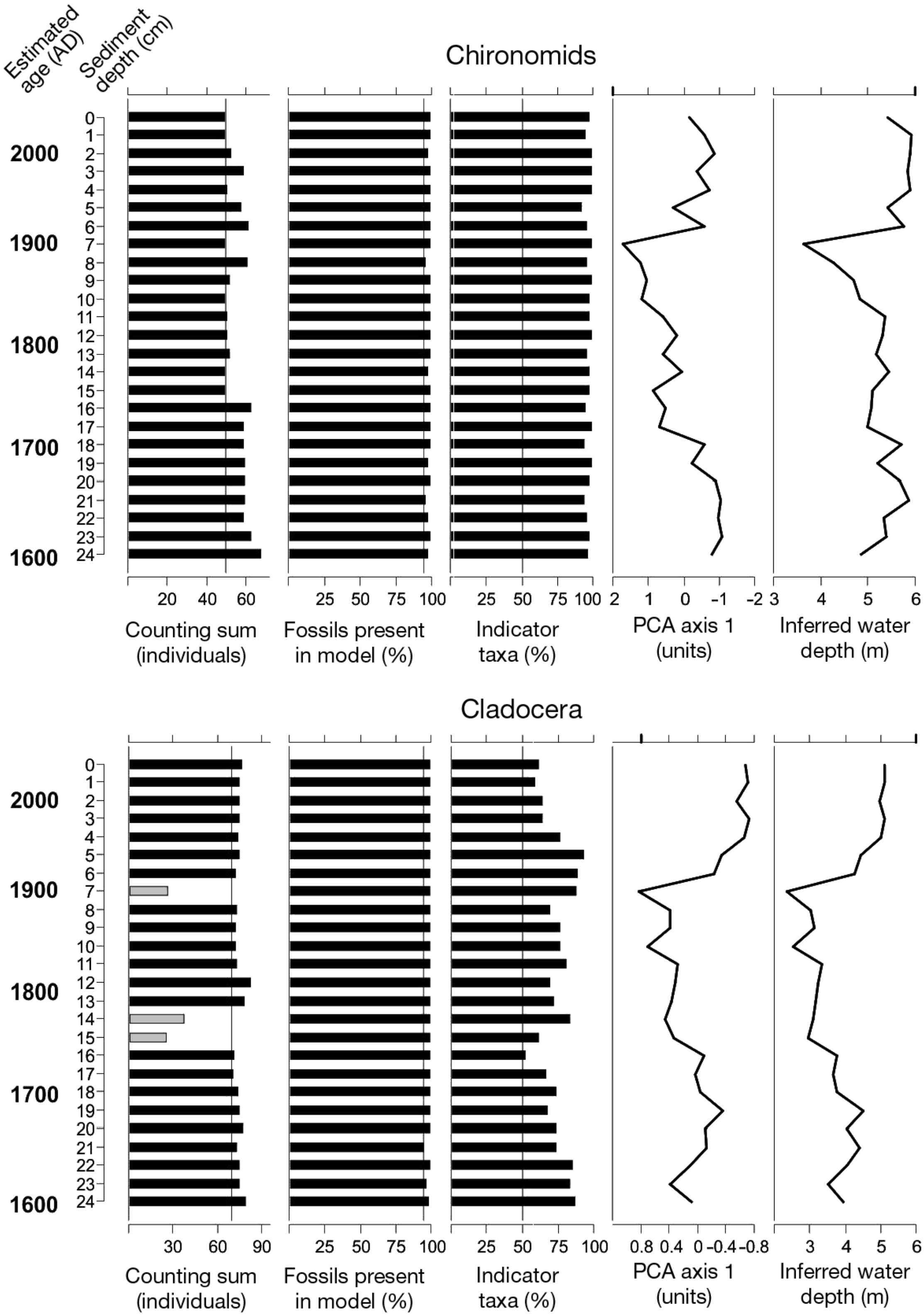

Fig. 4. Reconstruction reliability. Counting sum, representativeness of fossil samples in the calibration models, and PCA Axis 1 scores against the inferred water depth for fossil chironomids and Cladocera in the sediment core from Moaralmsee in the Niedere Tauern Alps, Austria. Representativeness is indicated by the columns 'Fossils present in the model', showing percentage coverage by the samples of fossil taxa present in the calibration set, and 'Indicator taxa', showing percentage coverage of taxa having a statistically significant relationship with water depth. Grey bars represent low counting sums in the Cladocera samples. The *x*-axes in the PCA Axis 1 scores are reversed for easier comparison with water level dynamics

Table 2. Pearson correlation matrix of the lake-level reconstructions based on different proxy records in the sediment profile from Moaralmsee in the Niedere Tauern Alps, Austria. All the relationships are significant (p ≤ 0.05). PCA: principal component analysis; LOI: loss-on-ignition

	Chironomid-inferred	Chironomid PCA Axis 1	Cladocera-inferred	Cladocera PCA Axis 1	Oribatid-inferred	LOI-inferred
Chironomid-inferred	1					
Chironomid PCA Axis 1	0.79	1				
Cladocera-inferred	0.74	0.71	1			
Cladocera PCA Axis 1	0.79	0.61	0.98	1		
Oribatid-inferred	0.55	0.45	0.74	0.76	1	
LOI-inferred	0.42	0.45	0.48	0.65	0.39	1

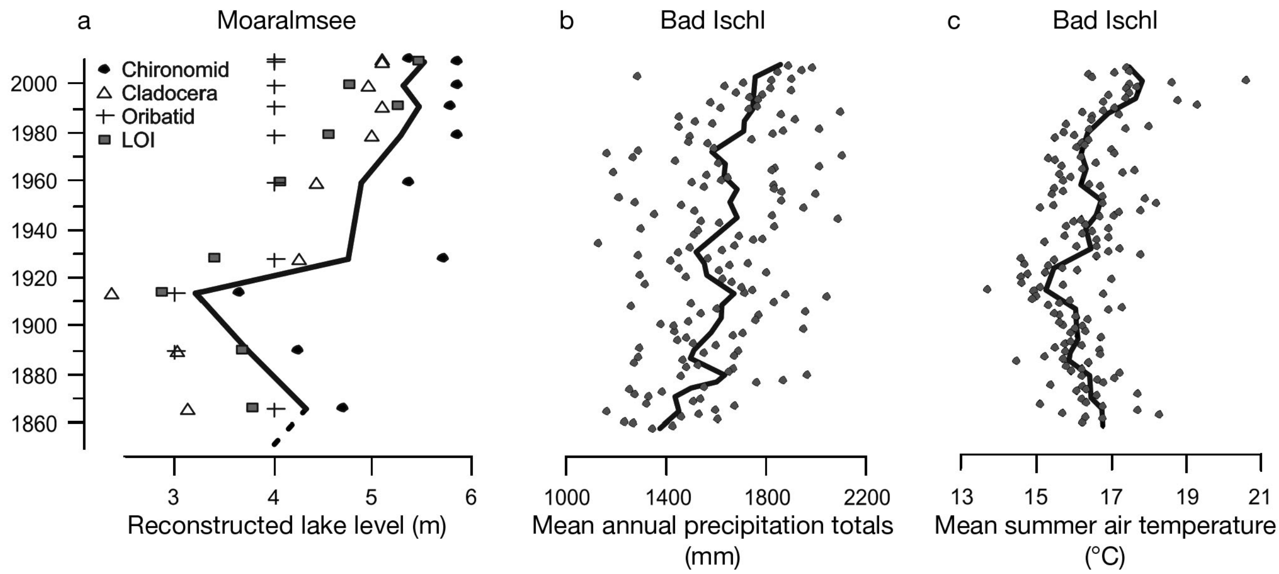

Fig. 5. Inferred and observed moisture. (a) Multiproxy reconstructions of lake-level changes (i.e. effective precipitation) in Moaralmsee (dashed line: time period that is not taken into account in the correlation calculations) and (b) instrumentally observed precipitation sums and (c) mean summer (June to August) air temperatures from an adjacent meteorological station in Bad Ischl over the observational period. In (a) the symbols represent the independent proxy records, whereas the line represents the combined multiproxy reconstruction. In (b) and (c) the lines represent observed data smoothed with a 20 yr low-pass filter

inferred water depths (Table 2, Fig. 4). In addition, there was a clear and significant ($p \leq 0.05$) relationship between all the lake depth reconstructions using the different proxies (Table 2). When the water depth reconstructions were compared with the observed precipitation data from an adjacent weather station, all the reconstruction, including the combined summary reconstruction, showed correlation with the observational record (Fig. 5). However, the chironomid- and oribatid-based reconstructions were not statistically significant at $\alpha = 0.05$ (Table 3). None of the proxy records suffered from statistically significant temporal autocorrelation that could influence the correlation calculations.

Table 3. Pearson correlations between the lake-level reconstructions based on different proxy records in the sediment profile from Moaralmsee and the instrumentally observed precipitation in Bad Ischl. The observed data are fitted into the chronological resolution of the Moaralmsee sediment core by using a running 20 yr mean. LOI: loss-on-ignition

	r	p
Chironomid-inferred	0.56	0.07
Cladocera-inferred	0.82	<0.01
Oribatid-inferred	0.55	0.08
LOI-inferred	0.75	<0.01
Combined reconstruction	0.75	<0.01

5. DISCUSSION

5.1. Proxy validation and reconstruction reliability

The Cladocera-based inference model of water depth developed from the intralake data from Moaralmsee using the PLS technique showed a strong relationship between the measured and inferred water depth (r = 0.85) (Fig. 2a). However, the samples at shallow depths (<3 m) were mostly overestimated by the model (Fig. 2b), suggesting potential problems when lake levels are very low, and the model performance statistics were not as good as with the chironomid-based model (Table 1). This was at least partly due to the fact that only 20 of the 31 samples were included into the cladoceran-based calibration model, whereas the chironomid-based model used 30 samples. Furthermore, there were only 5 Cladocera taxa present in the surface sediment data. Therefore, the chironomid-based training set probably provides more accurate water depth ranges and tolerances for the taxa, hence improving the model's performance statistics. Nevertheless, the RMSEP of the Cladocera-based model of 0.9 m and r^2_{jack} of 0.63 are adequate for a water depth inference model (Nevalainen et al. 2011a) and are good enough to justify the use of the Cladocera-based model to infer lake-level trends from downcore samples.The observed relationships between volumetric oribatid abundance and water depth and between LOI and water depth in the surface sediment dataset from Moaralmsee (Luoto 2012) also showed good potential for water depth assessments (Fig. 2c,d).

The chironomid- and Cladocera-inferred water depth for Moaralmsee showed similar trends (Fig. 3, Table 2). Furthermore, these changes corresponded closely with the changes detected in the oribatid- and LOI-based reconstructions (Fig. 3, Table 2). It is apparent from the results that the chironomid-based model inferred generally higher lake levels compared to the Cladocera-based model (Fig. 3). However, this divergence of ~1 m on average was consistent for the whole sediment record suggesting a consistent bias (Fig. 4, Table 2). Based on the inferred values for the surface sample, the chironomid-based reconstruction showed an underestimation of only 0.1 m, whereas the Cladocera-based model had a slightly larger underestimation of 0.4 m, which was, nevertheless, within the given modeling error. The larger bias in the Cladocera-based result suggests, however, that the chironomid results were quantitatively more accurate. This is supported by the reconstruction significance test, which showed that the chironomid-based reconstruction was statistically significant, whereas the Cladocera-based reconstruction was not. The reason why the Cladocera-based reconstruction failed the random TF test was probably due to the low number of taxa in the surface dataset and in the core data. In addition to the different reconstruction significance test results, chironomids had better coverage of indicator taxa represented in the core data than the Cladocera (Fig. 4). Furthermore, 3 of the Cladocera samples contained fewer taxa than were required for the sample to be representative of the living community; however lake levels inferred from these samples were not very different to the chironomid-inferred values.

Despite the consistent differences in the inferred values and apparent problems with the Cladocera-based reconstruction, the inferred trends were strikingly similar. In both cases, the inferred values were also very similar compared to the chironomid and Cladocera PCA Axis 1 scores (Fig. 4), providing evidence that these invertebrate communities did in fact respond to long-term lake-level changes at the examined site. The reason why the reconstructions based on chironomids, Cladocera, and oribatids had similar trends but differences in the numerical values is probably partly related to the fact that their responses to lake-level changes are most often indirect and mediated through other depth-dependent factors, such as oxygen availability and the temperature profile. It is known that chironomids are more sensitive to changes in oxygen and temperature regimes than Cladocera, which are more strongly influenced by factors related to productivity, habitat quality, and the food-web (Brodersen & Quinlan 2006, Nevalainen 2011, Luoto et al. 2013). However the fossil taxa in the core material were well represented in the both calibration sets (Fig. 4), providing further support for the reliability of both reconstructions in respect of their trends. The best way to test whether reconstructions are realistic is to compare them with observational records. In the present case, we compared our water depth reconstructions, hypothesized to indicate effective precipitation, against mean annual precipitation totals measured in a closely located weather station in Bad Ischl. All of the reconstructions, including the summary reconstruction, showed correlations with the instrumental record. However, the chironomid- and oribatid-based reconstructions were not significant (Table 3). This was most probably due to the time coverage of the observational record (from 1860 AD) since it was covered by only 10 sediment samples in our record. Furthermore, the oribatid-based polynomial regression model cannot predict water depths >4 m, because the model presumes that no oribatids are present at these depths (Fig. 2), which obviously hampers the correlation calculations.

In addition to the influence of water depth on contemporary faunal assemblages and substrate properties (Luoto 2012, Nevalainen 2012), chironomids, Cladocera, and LOI are also related to air temperature and water chemical characteristics in the Austrian, Italian, and Swiss Alpine lakes (Lotter et al. 1998, Bigler et al. 2006, Kamenik et al. 2007, Nevalainen et al. 2011b, Eggermont & Heiri 2012). Therefore, changes in regional factors, such as air temperature, or in local factors, such as trophic status, may at times influence the water level reconstructions in this study (cf. Nyman et al. 2008). In the Alps, atmospheric pollution may also influence the invertebrate communities (Nevalainen et al. 2011b) and hence the reconstructions. However, as all the reconstructions showed similar trends to the observed precipitation amounts, and in most cases a statistically significant correlation (Table 3), it can be deduced that the reconstructions are realistic and also that the current lake level record indicates changes in effective precipitation.

5.2. Alpine effective precipitation dynamics

The present multiproxy lake level records identified a period of low lake level from the base of the core, ca. 1600 until ca. 1650 AD, when the chironomid-based model inferred water depths of ~5 to 5.5 m and the Cladocera-based model depths of ~3.5 to 4 m. The oribatid- and LOI-based reconstructions were closer to the values inferred by Cladocera, suggesting that the lake level was probably closer to 4 m. Nevertheless, lake level was low during this period based on all the proxies. The initial period of low lake levels was followed by an increase in the inferred water depth. From ca. 1650 until ca. 1700 AD, water depth was ~5.5 to 6 m based on the chironomid model and ~4 to 4.5 m based on the Cladocera model. Within this period, oribatid-inferred depths (>4 m) were roughly similar to those inferred with chironomids. There was more variability in the LOI-inferred values, although these showed a similar increasing trend. In agreement with our reconstructions, Magny et al. (2011a) also showed that the water level was higher between ca. 1650 and 1700 AD in a lake in the Swiss Jura Mountains and Casty et al. (2005) reconstructed low annual mean Alpine (including Austria) precipitation for this time period based on long instrumental station data and documentary proxy evidence. According to summer temperature reconstructions for the European Alps based on tree rings, this period was characterized by low temperatures (Büntgen et al. 2005, 2006) and there is also evidence of glacier advance in Switzerland at this time (Holzhauser et al. 2005). This combined information on moisture changes and temperature variability suggest that this period, coinciding with the Little Ice Age, was cold and wet. This is also in agreement with the reconstructions from northern Europe (Luoto & Helama 2010).

In our record, a long period of lower lake levels was inferred between ca. 1700 and 1900 AD, with the chironomid-based reconstruction showing water depths of ~3.5 to 5.5 m and the Cladocera-based model depths of ~2.5 to 4 m (Fig. 3). The oribatid-inferred values were ~3 m for this period, while there was a decreasing trend in the LOI-inferred values from ~5 m at ca. 1700 AD to ~3 m at ca. 1900 AD. The lowest lake level during the entire sediment profile was inferred by both chironomid- and Cladocera-based reconstruction models at 7 cm, corresponding to ca. 1900 AD and the LOI-based reconstruction also showed its second lowest value in the same depth. Decreased lake levels were also reconstructed for this period from the Swiss Jura Mountains (Magny et al. 2011a) and, in addition, a decreasing trend in annual mean precipitation was shown by the Alpine instrumental and documentary data (Casty et al. 2005). The minimum inferred lake level at the end of the 19th century (Fig. 3) corresponds well with the decrease indicated by a testate amoeba-based water table reconstruction from a sub-alpine mire in Switzerland (Lamentowicz et al. 2010), hence suggesting decreased effective moisture during this period in the Alpine region. Since the instrumental record from Bad Ischl indicates decreased precipitation for this period (Fig. 5), it is very likely that the lake levels were low due to decreased precipitation. In addition, a general trend of increasing mean July air temperatures has been reconstructed from Switzerland for this period; the temperatures remaining cooler, however, than during the Medieval Warm Period, and than during the past century (Larocque-Tobler et al. 2010). In combination, these records indicate generally mild and dry climatic conditions for the Alps between ca. 1700 and 1900 AD.

Based on the lake level proxies, a period of elevated lake levels occurred from ca. 1900 AD until the present (Fig. 3). The chironomid-based inference model showed water depths of ~5.5 to 6 m and the Cladocera-based model depths of ~5 m. The oribatid-inferred values remained constantly >4 m during the last century but there was a progressively increasing trend in the LOI-inferred values. The rise in lake level contrasts with the reconstruction by Magny et al. (2011a) from the western Alps in Switzerland, which indicated lower lake levels for the last century. However, also from a Swiss record, Lamentowicz et al. (2010) showed a strongly increased mire water table from 1950 AD onwards, which is in agreement with the present reconstruction from the eastern Alps. Based on the precipitation records of Casty et al. (2005), a slight increase especially in winter precipitation was detectable for the last century when compared to the precipitation level between 1700 and 1900 AD in the Alpine region. In addition, mineralogical data by Trachsel et al. (2008) showed that, similarly to our reconstruction, the lake level began to increase at ca. 1850 AD in Lake Silvaplana, Swiss Alps. A trend of elevated winter precipitation based on measured data from Innsbruck, Austria, and retrodicted temperature data from the Tyrolean Alps has also been shown for the Alpine region (Koinig et al. 2002). The differences between some of the records are likely caused by the spatiotemporal variability in Alpine precipitation patterns. Furthermore, lakes have a tendency to respond differently to seasonal precipitation patterns, as water levels in individual lakes are affected more strongly by either winter or summer precipitation (Vassiljev 1998). It is well known that the temperatures have increased and glaciers retreated in the European Alps during the last century (Haeberli & Holzhauser 2003, Büntgen et al. 2005, Casty et al. 2005). Thus, it appears that the 20th century has generally been warmer and moister than preceding ones in the present study area. The present material does not indicate whether the increased lake level in Moaralmsee was caused solely by the increased precipitation observed from Bad Ischl or additionally by increased snow and ice melt in the catchment due to the increased summer air temperatures (Fig. 5). Nonetheless, our record of effective moisture suggests that the influence of increased precipitation overrides the influence of increased evaporation that is caused by the increased air temperatures.

For the most recent period (the late 20th and early 21st centuries), the inferred lake levels using the chironomid- and Cladocera-based calibration models showed elevated values, both indicating maximum lake level at 1 cm. This agrees with the field observations and the theoretical maximum depth of the basin, as the lake currently drains through an outlet. The theoretical maximum decreases in time as the basin fills with sediment, although in this case it has decreased by only 25 cm at the sampling point during the past ~400 yr. The theoretical maximum depth can be considered to act as a reference of reconstruction validity and, therefore, depths inferred above this level are most likely biased (Luoto & Sarmaja-Korjonen 2011). In the present data, all the samples had their eSEPs within the theoretical maximum depth, which in Moaralmsee is close to the present lake level.

Thompson et al. (2005) detected that the thermal properties of Moaralmsee are unusual, with summertime water temperatures generally 6 to 7°C cooler, compared to other Niedere Tauern lakes. They further suggested that, unlike other lakes, water temperature in the lake decreases when air temperature increases and attributed this to increased snow melt. Thus, in addition to higher winter precipitation at a regional scale (Koinig et al. 2002), the high modern lake level in Moaralmsee may also be a result of the recently increased temperatures leading to increased snow patch melt from the catchment (cf. Beniston 1997) and raising the water table (Luoto & Nevalainen 2012). During the time of the sampling in July, there were still small snow patches in the lake's catchment and it is possible that formerly snow patches covered a wider area of the catchment of the lake and thus constrained water inflow.

In addition to the chironomid- and Cladocera-based water depth reconstructions, the models based on oribatids and LOI showed consistent trends, thus confirming that these proxies can be useful in lake-level reconstructions. Although there appears to be some lag in the LOI-inferred water depths compared to the other proxies, the similar trends, reproducibility of results, and correlation with the 150 yr observational record suggest that the lake-level inferences are reliable. Furthermore, the results of this study provide evidence for the usability of intralake training sets based on fossil invertebrate assemblages and of modeling based on a single taxon (oribatids) and physical properties of the sediment (LOI) in an intralake training set. The results of the study will be valuable for setting baseline conditions for the study of present-day climate change, and contribute to a better understanding of precipitation dynamics and its spatial differences in the European Alps.

6. CONCLUSIONS

The present multiproxy results showed that simultaneous changes in the assemblages of fossil invertebrate remains and physical properties of sediments can be used to infer long-term lake-level fluctuations. The quantitative chironomid- and Cladocera-based water depth reconstructions showed strong correlation in their trends, and the same trends were also clearly reflected by the oribatid- and LOI-inferred water depths. The reconstructed trends were similar to the observed precipitation record from an adjacent weather station, confirming that the reconstructions were realistic, and that the lake-level changes corresponded to precipitation changes. In our reconstruction from Moaralmsee, lower lake level phases were inferred between ca. 1600 and 1650 AD and between ca. 1700 and 1900 AD, while high lake level phases were inferred between ca. 1600 and 1700 AD and from ca. 1900 AD until the present. In comparison to previous lake level records from the European Alps, the trends showed good general consistency. The present results provide invaluable information of past climatic variability in the Niedere Tauern Alps, but further long-term data are needed to verify the present reconstructions and to provide a more detailed picture of the long-term trends in the local and regional precipitation and temperature patterns in the Alps.

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