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DISSERTATION

Titel der Dissertation

Late glacial climatic and palaeoecological investigations of Längsee (Austria) using diatoms and chrysophyte cysts

angestrebter akademischer Grad

Doktorin der Naturwissenschaften (Dr. rer.nat.)

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Contents:

1. Introduction

The most dramatic climate changes are known from the period between the end of the last glaciation (= Würm in the Alps) and the beginning of the Holocene (approximately 20 – 11 cal kyr BP). Causes and impacts of the changes that occurred very rapidly during this time interval became of interest regarding present global warming (approximately 0.6 °C during the past century on a global scale and close to 1 °C since the early 1980s in the Alps; Beniston et al. 1997; Folland et al. 2001; Jones and Moberg 2003), although the latter is thought to be mainly men-made by the emission of greenhouse gases. According to the cyclicity of Pleistocene glacials and their similar patterns of deglaciation (Broecker 1984), the interval between approximately 20 and 11 cal kyrs BP is also called the last glacial termination or Termination I. Penck and Brückner (1909) established a concept of stepwise glacier retreats and advances from morains in the Alps for this period. Of all the classical alpine stadials, Gschnitz is presently assumed to have been the first glacier advance after the large alpine valleys became ice-free at about 16 cal kyrs BP (Ivy-Ochs et al. 2006).

Several indicators (called proxies) from lake sediments are used to reconstruct past climate change. Multidisciplinary (= multi-proxy) studies using quantitative inference models from indicator organisms such as diatoms (Schmidt et al. 1998, 2002b, 2004a; Lotter 2001), chrysophyte cysts (Kamenik et al. 2000; Schmidt et al. 2007), and chironomids (Lotter et al. 2000; Heiri and Lotter 2003; Millet et al. 2003; Heiri and Millet 2005) combined with pollen (Lotter et al. 1992a, 2000; Magny et al. 2001; Vescovi et al. 2007), stable oxygen isotopes from ostracods (von Grafenstein et al. 1992, 1999) and sediment parameters (Koinig et al. 2003; Schmidt et al. 2006, 2008) provide powerful tools for the reconstruction of climate change on different time scales (from hundreds of years to centennial and even decadal time scales). Many of these studies focus on the Holocene covering approximately the past 11,000 years. However, the application of these methods in lake sediments north of the Alps is hampered due to the fact that fossils are becoming scarce or lacking in sediments that are older than the Late Glacial Interstadial (lower boundary approximately 14 cal kyrs BP).

Längsee is a small meromictic lake (548 m a.s.l.; 46°45'45''N/14°25'10''E) in the Carinthian lowland of Austria (Fig. 1), which offers the unique opportunity to study fossil-bearing sediments that date back to early times of deglaciation. The lake lies south of the Alps close to the endmoraines of the former Drau glacier of the last glaciation (Würm) (Lichtenberger 1959; van Husen 1976, 1997). It was the first (Frey 1955, 1956) and most intensely investigated lake in Austria that was studied using palaeolimnological techniques. These studies focused mainly on (1) causes, developments and concepts of meromixis and (2) climate changes during late glacial times (Harmsworth 1984; Schmidt et al. 1998, 2002a, 2002b).

Fig 1: Längsee 2006
(Photograph: M. Pöttler)

Quantitative inference models based on **W**eighted **A**veraging (WA) regression and calibration are a powerful tool for inferring past environmental conditions from aquatic organisms (for summary see Birks 1998). The first step is to measure the modern abundance distribution of aquatic organisms (e.g. diatoms) from surface sediments or sediment traps of a sufficient number of lakes that cover a long gradient of the environmental variable of interest. These sites are called training set or calibration data set lakes. The environmental variable(s), such as water temperature or chemistry, are measured for the time of accumulation of the aquatic organisms in the surface sediments/sediment traps. As a second step, multivariate statistics is used to select the variable, which best (most significantly) explains the distribution of the aquatic indicator organisms in the training set lakes. Finally, a transfer function is established for this variable using WA-based techniques (e.g. WA-PLS, LWWA). The model output of species optima and tolerances obtained from the WA-equations are used to infer the environmental variable from the abundances of the aquatic fossils in the lake sediment archives (= dated sediment cores).

Diatoms are the most widely used biotic indicators in palaeolimnological studies, since they are usually abundant, diverse and well preserved in lake sediments (Smol and Cumming 2000). Due to their characteristic valve morphology, identification of diatoms to species level or even below is possible and documented by several standard taxonomical books such as Krammer and Lange-Bertalot (1986, 1988, 1991a, 1991b). Diatoms are long known to be sensitive primarily to pH (Hustedt 1930, 1937-39) and commonly, similar to most algae, nutrients (Lange-Bertalot 1978, 1979). They have been used as indicators of changes in these variables in numerous palaeolimnological reconstructions (e.g. Bennion et al. 1995; Bradshaw and Anderson 2001, Schmidt et al. 2002c). Although the direct influence of temperature on diatom growth is known from cultures (Montagnes and Franklin 2001), and diatoms show distinct distribution patterns along temperature altitude gradients (Lotter et al. 1997, Heegard et al. 2006), the impact of temperature on diatoms is yet suggested to be indirect (Anderson 2000). Probably it is mainly governed by the length of growing seasons enabled by warm and prolonged summers (e.g. Laing and Smol 2000, Keatley et al. 2008) and thus late mixing dates (Schmidt et al. 2004b). Even though the effect is indirect, a significant proportion of the variance in the species data is captured by summer temperatures independent from lake chemistry. Hence, diatom-based summer temperature models and transfer functions have been used as meaningful tools for the reconstruction of past climates (Pienitz et al. 1995; Weckström et al. 1997a, 1997b; Smol and Cumming 2000, Bigler and Hall 2003; Heiri and Lotter 2005).

Dating of late glacial sediments has to be considered with caution, mainly due to intervals with very low or reversed ^{14}C change with calendar age (Sarnthein et al. 2007). These atmospheric ^{14}C plateaus (Hughen et al 2004, 2006) probably result from changes in ocean circulation and CO_2 transfer from oceans to the atmosphere (Sarnthein et al. 2007). Furthermore, deposits from recently deglaciated catchments are particularly exposed to contamination by ^{14}C-deficient carbon from unvegetated bedrock (Sutherland 1980).

The overall goals of the thesis were (1) to quantitatively reconstruct lake water temperatures from fossil diatom assemblages of a sediment core from Längsee spanning the time of the last glacial termination between ca. 19,000 and 13,000 years ago, and (2) to put the inferred temperatures into a frame of climate change on a northern hemispheric scale. Commonly oxygen isotopes from Greenland ice-cores are used for climate comparison on a larger scale (Rasmussen et al. 2006, Andersen et al.

2006). In this case the oxygen isotope ($\delta^{18}O$) event stratigraphy from the Greenland ice-core GRIP that was adopted by Walker et al. (1999) was applied.

Since summer epilimnetic water temperatures (SEWT) were available for a large set of alpine and pre-alpine lakes spanning a temperature range of 18 °C, two previously published calibration data sets (Wunsam 1995; Wunsam and Schmidt 1995; Schmidt et al. 2004b) and new lake data sampled during the thesis were amalgamated to a super-set of 116 lakes (ALPS06). Multivariate statistical methods showed that SEWT was the most significant explanatory variable in ALPS06. A transfer function was generated for SEWT and applied to the fossil diatoms of the Längsee sediment core. The quantitative temperature inference also allowed a comparison of the aquatic record with the terrestrial response to climate obtained from pollen analysis in order to track common patterns and/or possible divergences/discrepancies. Finally, the results from Längsee were used for an evaluation exercise of climate patterns of the last glacial termination. Jeserzersee, a more shallow lake, about 32 km away from Längsee, was used as a reference to test if and how the same climatic trends are represented in different lake sediment archives.

Unfortunately, chrysophyte cysts were rare or lacking in the older sediments of the Längsee core and only well preserved and abundant in the core section of the Late Glacial Interstadial. A large number of cysts occurred that were not present in the calibration data set lakes of the Niedere Tauern (Kamenik & Schmidt 2005) and several cyst types were described as new. Thus, the idea of a quantitative temperature reconstruction was abandoned. Instead of this approach and in order to assess ecological preferences of chrysophyte cyst types, the cyst assemblage composition was compared with the diatom stratigraphy, diatom-inferred SEWT and total phoshorus. In the cyst stratigraphy of Längsee, one of the cyst types was replaced by another type with slightly different morphological features. This change in morphology is related to changes in the environmental conditions as indicated by the other proxies. The taxonomic position of these morpho- and/or ecotypes is, however, unclear. Wunsam et al. (1995) showed a similar pattern of morphotype differentiation for the *Cyclotella comensis* complex. Highly detailed morphological differentiation could be a way in palaeolimnology for a future fine-adjustment of diatom calibration. Hence, in this work, the ecological preferences of the different *C. comensis* morphotypes were determined in a sub-set of ALPS06 (86 lakes with a minimum of 1 % *C. comensis*) using gradient analysis (“HOF”, Oksanen and Minchin 2002).

Since some lakes included in ALPS06 were sampled more recently, the question arose if sampling during different time periods can cause inhomogeneity in a calibration dataset. For this reason, thermistor data measured during 1998/1999 and 2006/2008 in Unterer Wirpitschsee (1700 m a.s.l., Niedere Tauern), which is part of ALPS06, was used to track possible changes in the diatom and cyst assemblage composition in relation to water temperatures and chemistry during this time period, which is similar to the temporal sampling difference in the calibration data set.

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2. Publications

Distribution and morphological variability of *Cyclotella*-taxa in the late glacial of Längsee (Austria)

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pp 59-62

Kerstin Huber: Field work, taxonomy and stratigraphy of diatoms in Längsee, data analyses (except zonation), figures, writing

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INTRODUCTION

Längsee is a small meromictic lake (Löffler 1973) situated in the Carinthian lowland in Austria at an altitude of 548 m a.s.l. We have selected Längsee and the time interval of the Late-Pleniglacial and the older Late-Glacial (summarized here as “late glacial”), which approximately covers the time from 20 000 to 13 000 years before present, for several reasons: Since the lake is situated south of the Alps close to the end-moraines of the last ice age, fossil-bearing sediments date back to the time of deglaciation. Schmidt et al. (1998) described a warm period from Längsee, with an upper boundary of about 15 000 ^{14}C years, which was called “Längsee oscillation” (Schmidt et al. 2001). Data about this interstadial are, however, scarce in the Alps. Since future scenarios predict the disappearance of glaciers in the Alps during present global warming, studies of the development of pro-glacial lakes are of interest. In the present study we focus on the stratigraphic distribution and morphological variability of selected *Cyclotella*-taxa (*C. comensis* Grunow, *C. ocellata* Pant., and *C. distinguenda* Hust.) in comparison with related taxa.

MATERIAL & METHODS

The sediment core was taken in January 2006 with the UWITEC-Mondsee piston sampler (Schultze & Niederreiter 1990). Coring was performed from the ice at the lake’s maximum depth of 21.4 m. For sub sampling, the plastic tubes containing the sediment were cut into halves and sub-samples were taken at 0.5 cm intervals. For diatom analyses samples were prepared with 30 % H_2O_2 and 10 % HCl according to Battarbee (1986). Aliquot-evaporated suspensions were embedded in Naphrax. At least 500 valves were counted wherever possible using a light microscope (Leitz Laborlux S) with phase contrast oil immersion objectives (N.A. 1.32) at a magnification of 1250x. For dating we used AMS radiocarbon (^{14}C) dating from terrestrial plant macrofossils (Hajdas et al. 1993), mainly seeds from *Betula*. Diatom stratigraphies were zoned with constrained optimal sum of squares partitioning using the program ZONE (Juggins 1991).

RESULTS & DISCUSSION

Four zones were differentiated (Fig. 1). Below 430 cm (zone 1) no diatoms were found at all. Because of the age of ca. 20 000 years, it might represent the phase of deglaciation. It was followed by a period characterised by an assemblage of *Staurosira/Fragilaria*- and *Cyclotella*-taxa (mainly *C. comensis* MT1 according to Wunsam et al. 1995 and *C. ocellata).* It was interpreted as a time of warming, which, according to dating, most probably corresponds with the Längsee oscillation. During zone 2 benthic *Staurosira/Fragilaria*-taxa predominated at the expense of planctonic *Cyclotella*. According to Schmidt et al. (2004), many of these taxa are more frequent in coldwater lakes. Hence, it was interpreted as a period of climate deterioration. The zones 3 and 4 are characterised by an expansion of *Cyclotella*-taxa, which were also present in zone 1, but at lower abundances. *C. comensis*

MT 1 and *C. ocellata* are again the dominant taxa. In zone 4 *C. distinguenda* occurred more frequently. The zones 3 and 4 correspond to the older Late-Glacial. The boundary between the zones 2 and 3 was dated at ca. 14.5 kyrs before present (BP).

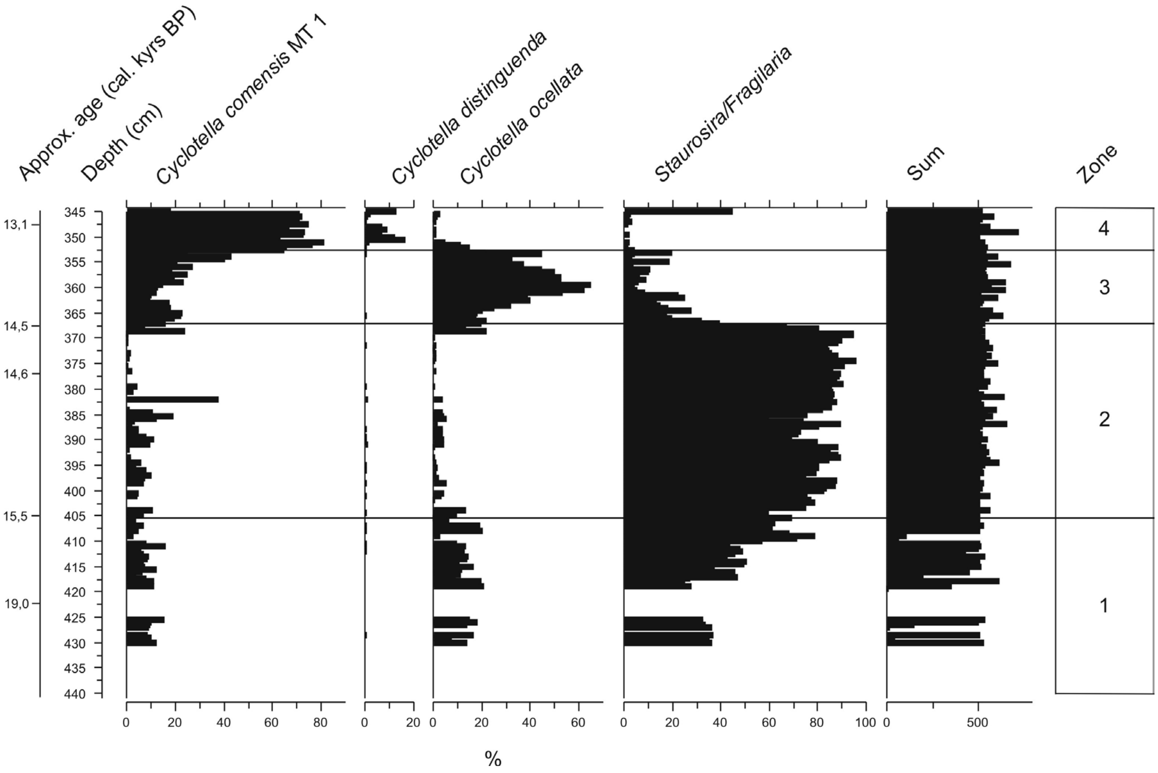

Fig. 1. Percentage diagram of selected diatoms in the Längsee core.

Wunsam et al. (1995) divided *C. comensis* from Alpine lakes into 4 morphotypes. Morphotype 1 (MT 1) was the dominant *C. comensis* type in our core section. It was described by Wunsam et al. (1995) as valves with a star-shaped central area with five or more radial depressions and elevations and the opening of one central fultoportula. The radial depressions of the central area commonly show smaller punctae, which, however, do not penetrate the siliceous wall. The marginal costae are of equal length and bear marginal fultoportulae on each second to sixth costa, visible with the openings at the outside valve (see also Håkansson 2002: fig. 349–351). Similar valves were described from a Swedish lake by Håkansson (2002: fig. 346–348) as *Cyclotella rossii* Håk., which is commonly distributed in subarctic lakes.

C. distinguenda and *C. plitvicensis* Hust. Are very closely-related taxa. According to Håkansson (2002), the major difference is that the central area of *C. plitvicensis* is flat and that of *C. distinguenda* is undulated (cf. Hustedt 1945). In the light microscope the undulation was not always clearly visible in the Längsee material, whereas in the SEM a slight undulation was detectable, especially when tilting the samples. According to Håkansson (2002), the central area of *C. distinguenda* is structureless, although sometimes a number of lines can be found in the depression of the undulation, appearing to be external wrinkles. These wrinkles could be found in valves of the Längsee core, but additionally the central areas could have punctae, which do not penetrate the siliceous cell wall. Such punctae have been described for *C. plitvicensis,* not for *C. distinguenda*. One rimoportula is located marginally, more or less radial, on one costa, which corresponds to *C. plitvicensis*.

C. plitvicensis is restricted to the highly oligotrophic Lakes Plitvice in Croatia, whereas *C. distinguenda* is a cosmopolitan (Krammer & Lange-Bertalot 1991) and wide spread in oligo- to mesotrophic lakes (Wunsam & Schmidt 1995). Since the major differential feature is the undulation of the central area in *C. distinguenda* (according to Håkansson 2002), all valves of the Längsee core were attributed to this species, although the punctae of the central area are confusing.

Cyclotella ocellata in Håkansson (2002) can have 3 to 5 (or even more) papillae and corresponding depressions in the central area. The depressions do not penetrate the siliceous wall. In the Längsee core valves with up to 7 depressions were found, but most had 3 to 5. All morphotypes occured in the same samples (Fig. 2). Hence it appears that the different morphotypes are not related to changes in the environment during the entire time window.

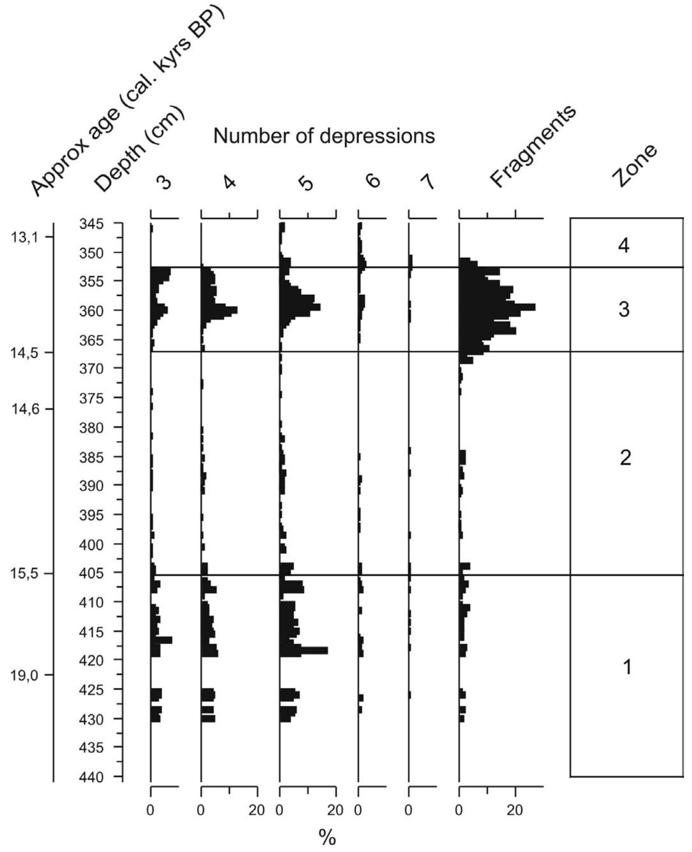

Fig. 2. Percentage diagram of different morphotypes of *Cyclotella ocellata* in the Längsee core.

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APPENDIX A

Taxonomic revision:

Critical *Cyclotella* taxa in the Längsee core were re-investigated after publication of the “Proceedings of the 1st Central European Diatom Meeting 2007” and compared with samples of the diatom calibration data set of Wunsam and Schmidt (1995).
The following Errata had to be adjusted:

Cyclotella comensis complex

Classification of *Cyclotella comensis* valves in the Längsee core was controversial in former studies (Schmidt et al. 1998, 2002). Comparison with *Cyclotella comensis* Grunow and *Cyclotella comensis* MT1 in the calibration data set of Wunsam and Schmidt (1995) showed that both types and intermediate valves were abundant in the Längsee core and could not be differentiated. Thus, both types were amalgamated and the name *Cyclotella comensis* was used later on for these valves of the Längsee core.

Cyclotella praetermissa/quadrijuncta complex

Comparison of *Cyclotella praetermissa/quadrijuncta* valves from the Längsee core with valves of the diatom calibration data set of Wunsam and Schmidt (1995) showed substantial differences in morphology. The valves found in Längsee are similar to those described by Klee et al. (1993) from sediments of the Alleröd period in the lakes Starnberg, Ammersee (Bavaria) and Höllerer See (Upper Austria), and which they called *C.* aff. *quadrijuncta*. Hence, this name was used later on for the valves from Längsee.

Cyclotella distinguenda complex

In the Längsee core, all valves of this complex show an undulation of the central area, which, according to Håkansson (2002), is the major characteristic of *Cyclotella distinguenda*. The slight undulation is visible only in the SEM. In LM, the majority of valves in the Längsee core is nearly flat. These valves show punctae in the central area, which is a feature attributed to *Cyclotella plitvicensis*. Hence, valves with a minor undulation and punctae in the central area were called *Cyclotella* aff. *plitvicensis* and were separated from *Cyclotella distinguenda* valves (clearly undulated central area and no punctae) later on.

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Climate changes during the last glacial termination inferred from diatom-based temperatures and pollen in a sediment core from Längsee (Austria)

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Key words: Alpine lakes, diatoms, temperature transfer function, pollen, deglaciation

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<u>Kerstin Huber</u>: Field work, taxonomy and stratigraphy of diatoms in Längsee, data analyses (except zonation), figures, writing

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ORIGINAL PAPER

Climate changes during the last glacial termination inferred from diatom-based temperatures and pollen in a sediment core from Längsee (Austria)

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Ruth Drescher-Schneider · Johann Knoll ·
Jutta Schmidt · Roland Schmidt**

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Abstract A sediment core section from Längsee, a small meromictic lake in the southern Alpine lowland (Carinthia, Austria) close to the Würmian ice-margin, was investigated by means of diatoms and pollen. The main aims of the study were to reconstruct water temperature as a signal of climate change during the last glacial termination, compare the aquatic and terrestrial response to the changing climate, and place our findings into a climatic frame on the northern hemispheric scale. A calibration data set (ALPS06) of 116 lakes was constructed using data from newly studied lakes and from two previously published data sets and we established a transfer function for predicting summer epilimnetic water temperatures (SEWT). A locally weighted weighted average regression and calibration model (R^2_{jack} = 0.89; RSMEP = 1.82°C) was applied to the fossil diatom assemblages in order to reconstruct SEWT. Three major sections were distinguished in the time window of approximately 19–13 cal kyear BP, which fitted well with the oxygen isotope curve and the isotope-event stratigraphy from the Greenland ice-core GRIP. The first section was a warming period (SEWT range from 11.6 to 18.0°C; average 15.8°C = ca. 6°C below present) called the Längsee oscillation, which probably correlates with the warmer sub-section (GS-2b) of the Greenland Stadial 2. The subsequent section represents a climate cooling, called the Längsee cold period (SEWT range between 10.6 and 15.9°C; average 12.9°C), which probably corresponds with the sub-section GS-2a of the Greenland Stadial 2, the Heinrich 1 cold event of the North Atlantic, and partially the Gschnitz Stadial in the Alps. The Längsee cold period shows a tripartition: Two colder phases are separated by a warmer inter-phase. The passive ordination of the core sample scores along maximum water depth indicated that the Längsee cold period was drier than the Längsee oscillation. Strong short-term fluctuations during the Längsee oscillation and the Längsee cold period indicate climate instability. The third section represented climate warming during the Längsee late glacial interstadial (=Greenland Interstadial 1, GI-1) with an average SEWT of 17.5°C. From the minor climatic fluctuations during this interstadial, mainly indicated by pollen, the fluctuation most likely related to the Gerzensee oscillation showed a SEWT decline. During the early immigration and expansion period of shrubs and trees, aquatic and terrestrial records showed

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distinct discrepancies that might have arose because of time lags in response and differences in sensitivity.

Keywords Alpine lakes · Diatoms · Temperature transfer function · Pollen · Deglaciation

Introduction

The last glacial termination, spanning the time between ca. 21 and 11.5 cal kyear BP, is known as a transition from the full glacial mode of the Last Glaciation to the interglacial state. Climate changes of the late glacial interstadial (ca. 14.5–11.5 cal. kyear BP) are well documented by paleobotanical analyses (Lotter et al. 1992a; Björck et al. 1996), oxygen isotopes in lacustrine carbonates (von Grafenstein et al. 1999), and organisms from lake sediments such as diatoms and chironomids including the use of quantitative inference models also called transfer functions (Wunsam 1995; Heiri and Millet 2005). However, less is known about the preceding times since the beginning of the Würmian glacial retreat. The main reason for this is that most of the alpine lake sediments are too young and only a few sediment records are slightly older than the late glacial interstadial (Schmidt 1975; Avigliano et al. 2000; Drescher-Schneider et al. 2007; Vescovi et al. 2007). Längsee, a small meromictic lake in Austria, lies close to the end moraines of the Last Glaciation (Lichtenberger 1959; van Husen 1976, 1997). Consequently, it offers the unique opportunity to study fossil-bearing sediments, which date back to times of deglaciation (Schmidt et al. 1998, 2002a, b). Previous investigations indicated a warming period within the pollen zone of the Oldest Dryas (Firbas 1954), which was called Längsee oscillation (Schmidt et al. 2001). Oxygen isotope records from Greenland ice-cores (Rasmussen et al. 2006; Andersen et al. 2006) indicated a succession of cold and warm periods during the last glacial termination, which support the findings from Längsee.

In the present study we infer climate changes during the time of approximately 19–13 cal kyear BP in Längsee at a significantly higher time resolution than previously studied, and place our findings in a climatic frame on a larger, northern hemispheric scale. We use mainly terrestrial plant macrofossils for AMS radiocarbon (^{14}C) dating, and establish a diatom-based summer epilimnetic water temperature (SEWT) transfer function by amalgamating three data sets from the Alps (Wunsam 1995; Wunsam and Schmidt 1995; Schmidt et al. 2004b; and some new data). We then apply this transfer function to the fossil diatom assemblages of the Längsee sediment core. Although the impact of temperature on diatoms is thought to be equivocal (Anderson 2000; Battarbee 2000; Schmidt et al. 2004a), temperature has been shown in several studies to capture a significant proportion of the variance in the species data independent of lake chemistry (Pienitz et al. 1995; Lotter et al. 1997; Weckström et al. 1997a, b; Rosén et al. 2000; Bigler and Hall 2003), and hence was used to infer past climate changes. We also compare the diatom-inferred SEWT with the pollen record and with the oxygen isotope curve from the Greenland ice-core GRIP (Rasmussen et al. 2006; Andersen et al. 2006) using the GRIP-based isotope-event stratigraphy from Walker et al. (1999).

Study area

Längsee (548 m a.s.l.; 46°45’45’’N/14°25’10’’E), is a small (0.75 km^2), 21.4 m deep, meromictic, lake, located in the Carinthian lowland of Austria. The lake lies in the Würmian Drau glacier retreat area, close to the Würm pleniglacial ice margin (Lichtenberger 1959; van Husen 1976, 1997). Today Längsee is an oligo/mesotrophic lake that warms distinctly during summer (Table 1).

Table 1 Characteristics of the ALPS06 training set lakes (116) and Längsee 2006 (Kärntner Seenbericht; Schulz 2007)

	Unit	Training set of 116 lakes			Längsee
		Mean	Median	Range	
Altitude	m a.s.l.	1154	749	194 – 2309	548
SEWT	°C	14.6	16.8	4.0 – 22.0	21.7*
pH		7.8	8.1	6.9 – 8.6	8.4
COND	μS_{25} cm^{-1}	205	214	12 – 489	378
TIN	µeq l^{-1}	30.6	17.6	0.1 – 310.0	67.2
TP	µg l^{-1}	12.6	7.0	1.0 – 266.0	9.0
MD	m	33.0	17.9	2.1 – 370.0	21.4

* Average of the years 2002–2006. Abbreviations: *SEWT* summer epilimnetic water temperature, *COND* conductivity, *TIN* total inorganic nitrogen, *TP* total phosphorus, *MD* maximum depth

Materials and methods

Coring and dating

The 2-m long sediment core LAE06 was taken from Längsee in January 2006 with a modified Kullenberg piston sampler (Schultze and Niederreiter 1990) at the deepest point of the lake. After cutting the 9-cm diameter plastic tubes into halves following Schmidt et al. (2002a), sub-samples were taken at consecutive 0.5-cm intervals from the core section between 340 and 440 cm depth.

Seven AMS radiocarbon (^{14}C) dates were obtained from terrestrial plant macrofossils, which were mainly seeds of *Betula* (Hajdas et al. 1993). They were dated by the University of Kiel, Leibniz-Laboratory for Radiometric Dating and Stable Isotope Research. Because of low numbers of terrestrial plant macrofossils, consecutive samples were used to provide enough material for dating. In some cases, however, additional indefinite plant remains had to be used. Radiocarbon dates were calibrated using the data set Intcal04 in the CALIB rev 5.01 program (Stuiver and Reimer 1993).

Diatom analysis

Chemical treatment of samples with acid digestion (HCl, H_2O_2) and preparation of diatom slides with Naphrax mountant followed Battarbee (1986). With the exception of the lowermost part of the core with very low diatom concentrations, at least 500 diatom valves were counted using a light microscope (Leitz Diaplan) with 100x phase contrast oil immersion objectives (N.A. 1.32) and a magnification of 1250x.

The diatom stratigraphy was plotted using the computer program C2 1.5 (Juggins 2007). For the zonation of the diagram, we applied constrained optimal sum of squares partitioning using the program ZONE (Lotter and Juggins 1991). The number of statistically significant zones was calculated using the broken-stick model described in Bennett (1996). The same was done for terrestrial pollen and aquatic macrophytes.

Wunsam et al. (1995) differentiated four additional morphotypes of *Cyclotella comensis* Grunow in van Heurck and outlined their diverse ecological preferences. In LAE06 *C. comensis* and morphotype MT1, showing a radial punctate ornamentation of the central area, could not be distinguished (Schmidt et al. 1998, 2002b). Hence, we amalgamated both morphotypes, which we called *C. comensis* in this study. This was also done in ALPS06. Morphotype MT2, with a colliculate ornamentation of the central area, which was less abundant in LAE06 than the former, was clearly distinguished. The major difference between *C. plitvicensis* Hustedt and *C. distinguenda* Hustedt, according to Håkansson (2002), is the flat central area in *C. plitvicensis*. In a sediment core from Lake La Cruz, Spain, Kiss et al. (2007) found a large morphological variability in valves, which they assigned to *C. distinguenda*. In LAE06, valves, which showed a nearly flat central area with scattered punctae, were distinguished from *C. distinguenda*, and were called *C.* aff. *plitvicensis* (Schmidt et al. 2002b). At present *C. plitvicensis* is restricted to Lake Plitvice in Croatia. Recently, however, a taxon was found in Lustsee (Bavaria), which is comparable to *C. plitvicensis*, and resembles the valves found in Längsee (R. Klee, personal communication). Similar to Lake Plitvice, Lustsee is a highly oligotrophic, hardwater lake (Table 2). Lustsee was used in the calibration data set. In LAE06, *Cyclotella* valves were found, which have previously been described by Klee et al. (1993) from sediments of the Alleröd period in the lakes Starnberg, Ammersee (Bavaria) and Höllerer See (Upper Austria), and which they called *C.* aff. *quadrijuncta*. No modern analogue for this taxon was found in the calibration data set. Identification of *Staurosira* taxa followed mainly Schmidt et al. (2004b).

Diatom-based temperature reconstruction

Calibration data set

Because of marked shifts in the diatom assemblages of LAE06, a great variety of lakes was needed for the calibration data set, in order to cover all major diatom taxa. Therefore, we amalgamated three diatom calibration data sets: (1) Parts of the calibration data set of Wunsam (1995) and Wunsam and Schmidt (1995) consisting of 86 alpine and pre-alpine lakes in Austria, Germany and northern Italy. The 66 lakes from the data set with a minimum of four measuring dates for mean SEWT were included in this study. (2) The calibration data set of Schmidt et al. (2004b) consisting of 40 Austrian alpine lakes. (3) The 10 additional lakes were sampled in 2006/2007 (Table 2) following the procedures described by Schmidt et al. (2004b). In total, the calibration data set (ALPS06) consists of 116 lakes. In addition to SEWT, the following variables exist for all lakes: pH, conductivity (COND), total inorganic nitrogen (TIN), total phosphorus (TP) and maximum depth (MD).

Multivariate statistics

All environmental variables were tested for skewness and, in the case of TIN, TP and MD, $\log_{10}(x + 1)$ transformed. Diatom abundances were always square-root transformed to stabilize their variances. Detrended correspondence analysis (DCA; Hill and Gauch 1980) with detrending-by-segments and down-weighting of rare species of the diatom assemblages (DA) resulted in a gradient length of 4.3 standard deviation (SD) units of species turnover, suggesting unimodality of the species data (ter Braak 1987; Birks 1995). Therefore, we used canonical correspondence analysis (CCA; ter Braak 1986), an ordination technique that assumes a unimodal species response with forward selection and associated Monte Carlo permutation (999 unrestricted permutations, $P \leq 0.01$) to test the significance of the explanatory variables. The independent explanatory power of these variables was tested by variance partitioning (Borcard et al. 1992). Ordination analyses were performed using the program CANOCO 4.5 (ter Braak and Šmilauer 2002). For quantitative diatom-based inferences of the measured variables, weighted averaging (WA), weighted averaging—partial least squares (WAPLS) and locally weighted weighted averaging (LWWA) regression and calibration were applied using the program C2 1.5 (Juggins 2007). All three models performed very similarly in terms of reconstruction statistics (R^2, RMSEP, maximum bias). LWWA, a method using a so-called ‘‘local’’ training set, which is a subset of the original training set for each core sample, was favoured because of great shifts between benthic and planktonic taxa in the diatom assemblages of the sediment core. The local training set in LWWA consists of a selected amount (in our case 30 lakes) of closest analogues to the species assemblages in each core sample. One sample with large residuals (5 SD units) along the gradient was deleted from the model as an outlier (Simssee). The cross-validation technique

Table 2 Chracteristics of the 10 lakes used in Alps06 sampled 2006/2007

Unit	Ahornsee (47°28’00“N-13°46’56“E)	Augstsee (47°39’49“N-13°47’10“E)	Grafenbergsee (47°28’01“N-13°46’04“E)	Laserzsee (46°46’44“N-12°48’10“E)	Lunzer See (47°51’13“N-15°03’11“E)	Lustsee (47°48’37“N-11°17’45“E)	Mönichsee (47°46’06“N-13°27’12“E)	Simssee (47°52’22”N-12°14’22”E)	Steirersee (47°35’56”N-14°01’54”E)	Vorderer Lahngangsee (47°40’15”N-13°55’50”E)
Altitude (m a.s.l.)	1,485	1,643	1,643	2,260	605	588	1,300	470	1,445	1,494
SEWT (°C)	15.1	13.1	14.1	9.4	14.4	18.0	11.2	21.6	14.3	12.5
pH	8.2	7.7	8.4	8.7	8.0	7.9	8.3	8.2	8.4	8.5
COND (μS_{25} cm^{-1})	213	122	213	121	214	460	172	352	213	153
TIN (μeq l^{-1})	5.5	7.1	3.9	19.5	51.2	63.3	34.5	35.0	5.4	18.7
TP (μg l^{-1})	11.2	8.3	9.6	3.0	5.8	6.0	6.4	24.1	7.3	5.5
MD (m)	11.5	8.2	20.0	10.0	34.0	18.0	34.0	22.0	20.0	78.0

Abbrevations: *SEWT* summer epilimnetic water temperature, *COND* conductivity, *TIN* total inorganic nitrogen, *TP* total phosphorus, *MD* maximum depth leave-one-out was used to give a more realistic estimation of the model performance.

Pollen and non-pollen palynomorph analysis

For pollen and non-pollen palynomorph (NPP) analyses, 1 cm^3 of fresh material was treated according to the method described in Schmidt et al. (2002a). A sum of 600–1,000 pollen grains was counted in each sample. Identification of pollen and NPP types based mainly on Beug (2004) and the reference collection of R. Drescher-Schneider. The nomenclature of the known and already described NPP conforms to that of Bas van Geel (University of Amsterdam). The unknown NPP were described and presented in photos and drawings (Fig. 1).

Results

Dating

The selected core section covers a time window from 11,115 ± 49 ^{14}C year BP (=ca. 13.2–13.0 cal kyear

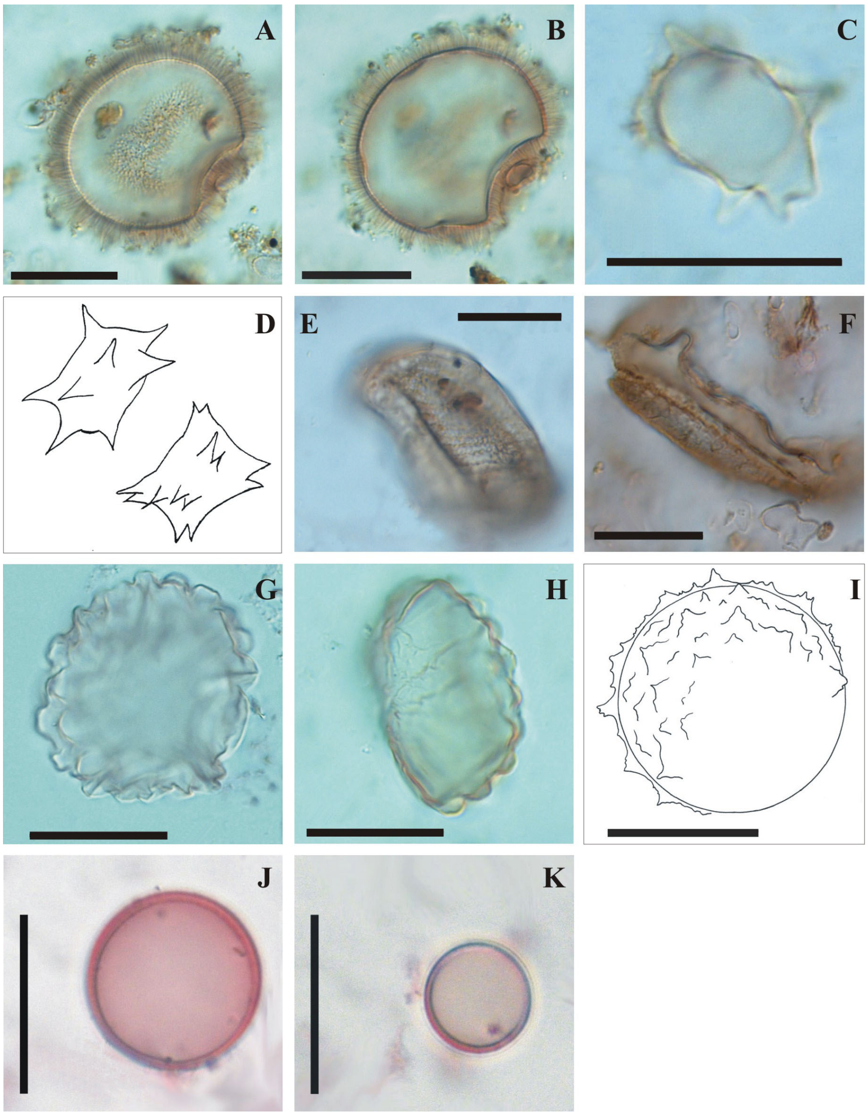

Fig. 1 Selected non-pollen palynomorphs (*NPP*) in LAE06: **a**, **b** Type R 24; **c**, **d** Type R 31; **e**, **f** Type R 66; **g**, **h** Type R 70; **i** Type R 65; **j**, **k** *Coccus nivalis*. *Scale* shows 20 µm

Table 3 AMS radiocarbon (^{14}C) dates from LAE06

Lab code	Depth (cm)	Material analysed	Weight (mg)	δ^{13}C (‰)	^{14}C age BP	Cal ^{14}C age BP (1σ range)	Cal ^{14}C age BP (2σ range)
KIA30599	346-347	17 *Betula* seeds, 6 *Betula* scales, 4 *Carex* seeds, 15 leaf fragments (indet.), 1 needle fragment (indet.)	4.4	-27.2	11115 ± 49	13127-13015	13170-12969
KIA30225	365-367	20 *Betula* seeds, 5 *Betula* scales, 1 *Betula* leaf fragment, 2 *Juniperus* needles	2.0	-26.0	12414 ± 57	14650-14273	14889-14195
KIA30226	375-377	3 wood fragments (indet.)	4.6	-26.8	12467 ± 48	14752-14349	14952-14264
KIA30227	380-383	6 *Betula* seeds, 2 *Betula* scales, 1 *Carex* seed, 5 leaf fragments (indet.), 2 wood fragments (indet.)	1.2	-28.1	13059 ± 74	15641-15295	15854-15170
KIA30228	397-401	4 *Betula* seeds, 7 *Betula* scales, leaf fragments (indet.)	0.9	-28.9	11362 ± 76	13348-13216	13418-13151
KIA30229	403-407	2 *Betula* seeds, 1 *Betula* scale, 3 leaf fragments (indet.), 4 leaf stem fragments (indet.)	0.6	-25.9	13015 ± 109	15613-15226	15853-15081
KIA30230	420-425	1 *Carex* seed, 2 leaf fragments (indet.), 3 leaf stem fragments (indet.)	1.4	-16.9	15715 ± 88	19052-18920	19150-18840

BP) to 15,715 ± 88 ^{14}C year BP (=ca. 19.2–18.8 cal kyear BP; Table 3). It is divided into a varved, organic sub-section between 344- and 367-cm depth, and an unvarved, minerogenic sub-section below 367 cm (Schmidt et al. 2002a). The ^{14}C date of 12,414 ± 57 year BP (=ca. 14.9–14.2 cal. kyear BP) is close to this boundary and the volcanic tephra of the Neapolitan Yellow Tuff (NYT), which was detected at 365.5-cm depth (A. Brauer, personal communication). In the minerogenic sub-section, terrestrial plant remains (mainly *Betula*) decreased drastically explaining the low number (5) of ^{14}C dates.

Diatom stratigraphy

The diatom distribution of LAE06 showed the following four major zones and eight sub-zones (Fig. 2).

Zone D1 (440–404.5 cm)

Below 430 cm (D1/1) no diatoms were found. They were also missing between 419 and 425 cm (D1/3). In the sub-zones D1/2 and D1/4, the occurrence of diatoms was variable. Overall, zone 1 was characterised by planktonic *Cyclotella*-taxa mainly *C.* aff. *quadrijuncta*, *C. comensis* morphotypes, *C. distinguenda* var. *unipunctata* (Hustedt) Håkansson and Carter, *C. ocellata* Pantocsek together with benthic *Staurosira*-taxa particularly *S.* aff. *venter* (Ehrenberg) Cleve and Moeller, *S.* (*Fragilaria*) *brevistriata* Grunow, *S.* (*Fragilaria*) *pinnata* Ehrenberg morphotypes. The percentage of unidentified *Cyclotella* valves was high in this section due to the bad preservation.

Zone D2 (404.5–366 cm)

Zone D2 was dominated by *Staurosira*-taxa. The most abundant taxon was *S.* aff. *venter* accompanied by *Amphora pediculus* (Kützing) Grunow (D2/1). In the upper half of zone D2 the relative abundance of *S. brevistriata* increased (D2/2).

Zone D3 (366–351.5 cm)

This section was characterised by an increase in *Cyclotella*-taxa, which were also present in zone D1, but at lower abundances. The dominant species was *C. ocellata* together with *C. comensis* morphotypes, *C.* aff. *quadrijuncta*, and *C. distinguenda* var. *unipunctata* in the lowermost part (D3/1), and with *Asterionella formosa* Hassall, *C. cyclopuncta* Håkansson and Carter and *C. kuetzingiana* Thwaites in the upper part (D3/2).

Zone D4 (351.5–344 cm)

Zone D4 differed distinctly from the former by the dominance of *C. comensis* morphotypes and an

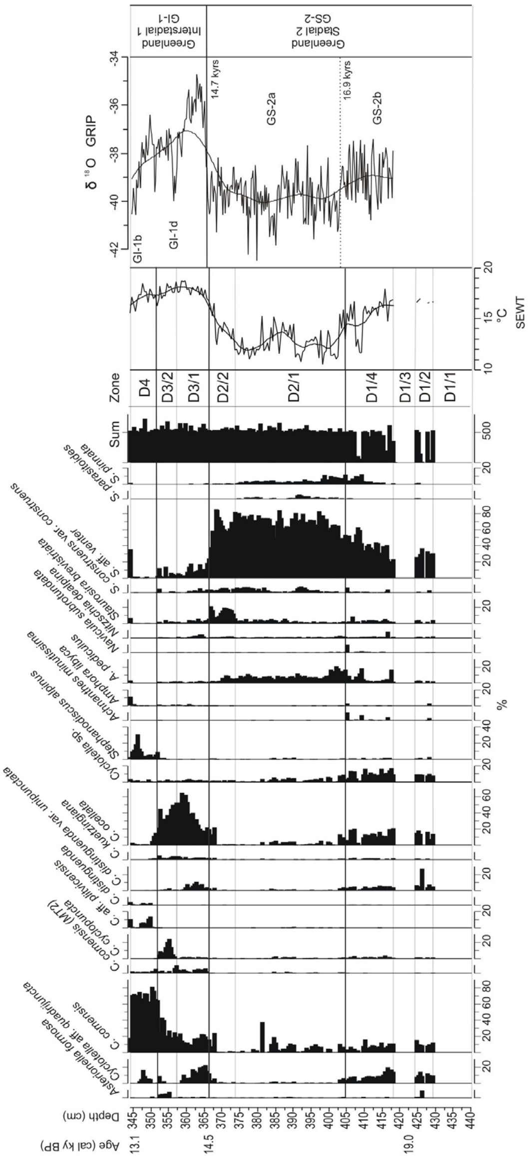

Fig. 2 Percentage abundance diagram of selected diatoms in LAE06, diatom zones (*black lines*) and sub-zones, diatom-inferred summer epilimnetic water temperature (*SEWT*), the GRIP oxygen isotope curve from Greenland (Rasmussen et al. 2006, Andersen et al. 2006) and the isotope-event stratigraphy from Walker et al. (1999)

increase in *C. distinguenda*, *C.* aff. *plitvicensis* and *Stephanodiscus alpinus* Hustedt in Huber-Pestalozzi, at the expense of *C. ocellata*.

Table 4 Descriptive statistics of the diatom training sets ALPS06 and performance of the temperature inference model (SEWT) after deletion of one outlier

	SEWT
Number of samples	116
Number of taxa	560
N_2 for taxa	
Minimum	1.00
Median	3.87
Maximum	72.82
Range of SEWT in ALPS06	
Minimum (°C)	4.0
Mean (°C)	14.6
Median (°C)	16.8
Maximum (°C)	22.0
Prediction model	LWWA Cla
R^2 (apparent)	0.97
RMSE (apparent) (°C)	0.99
R^2 (jackknifed)	0.89
RMSEP (jackknifed) (°C)	1.82
Max bias (jackknifed) (°C)	4.1

Multivariate statistics

The five forward-selected variables mean SEWT, pH, COND, TP and MD accounted for significant and independent fractions of variation and explained altogether 21.6% of the observed variation in the diatom data. The variance explained is relatively low, but it is typical of data sets containing many taxa and many zero values in the species matrix. The associated permutation tests, however, show statistical significance of the explanatory variables. The ordination axes 1 and 2 were both statistically significant ($P \leq 0.01$) and accounted for 12.8 and 3.7% of the variance in the species data, respectively, with eigenvalues of 0.674 and 0.190. The environmental variables SEWT, pH, COND and TP showed inter-set correlations ranging from -0.74 to -0.92 with the first axis, while MD showed an inter-set correlation of 0.65 with the second axis. We established regression and calibration models for the five forward-selected environmental variables. When environmental variables are highly correlated in the modern calibration data set, they generally produce similar down-core reconstructions. In some cases the reconstructed variables may have changed simultaneously over time, however, in other cases it may have been that only one variable has changed, but due to present-day correlations in the calibration data set, other variables follow this pattern. Hence it is advisable, when such correlations exist to reconstruct one variable that has the most robust model and is ecologically meaningful. Based on these criteria we chose SEWT. It had the best prediction model of all environmental variables in the training set with an R^2_{jack} of 0.89 and a RSMEP of 1.82°C. Descriptive statistics of the calibration data set and the inference model are summarized in Table 4.

Diatom-inferred summer epilimnetic water temperature

For zone D1, an average SEWT of 15.8°C was inferred. Temperature fluctuations were high, ranging from 11.6 to 18.0°C. In zone D2, the SEWT was distinctly lower (mean 12.9°C) and characterised by several short-term fluctuations resulting in a temperature range from 10.6 to 15.9°C. During zone D3, average SEWT increased to 17.8°C. In zone D4, the average SEWT decreased slightly to 17.1°C (Fig. 2).

Pollen and non-pollen palynomorph analysis

A 122 pollen and 23 NPP types were identified. The unknown NPP (numbered as Type R xx), which are important for the zonation of the pollen diagram, are presented in the following description, as well as in photos and drawings (Fig. 1).

Type R 24 (Fig. 1a, b): globose hyaline microfossil, 25–40 µm in diameter, exclusive to the appendages on the approximately 0.5-cm thick wall, which are 7–8 µm long, <0.5 µm wide and have a small swelling at the end. The distances between the bases of the appendages are ca. 0.5 µm or less. Because of the thin wall, the microfossil is often broken or folded. This type is similar to type G 232 (van Geel et al. 1989), but the size is smaller, the appendages are longer, thinner and denser.

Type R 31 (Fig. 1c, d): ellipsoid hyaline microfossil, approximately 10 x 20 µm, exclusive of the 8–16 spines, 4–7 µm long and 2–4 µm broad on the bases. Depending of the position and the size of the spines, the object may be of a more rectangular form.

Type R 65 (Fig. 1i): globose hyaline microfossil. Inner wall approximately 0.5 µm thick, external wall thinner and forms spine-like processes of different size and irregular distribution. In general this type is folded due to the thin and unstable wall.

Type R 66 (Fig. 1e, f): light brown boat-shaped microfossil. 20–25 x 40–50 µm. The most characteristic marks are small strips (thickenings) at the thicker/swollen dorsal side. The ventral side is open (broken?). It is most probably of animal origin.

Type R 70 (Fig. 1g, h): circular to subtriangular spore, ±35 µm in diameter and ±20 µm thick. The proximal face is covered by circular, rounded protuberances, the distal side with star-shaped folds starting from the centre. It could belong to snow algae (J.-N. Haas, personal communication).

‘‘*Coccus nivalis*’’ (Fig. 1j, k): globose microfossil, 10–25 µm, partly with <0.5 µm long spines, but in general without and often with a S-shaped furrow. This type has been described the first time by Klaus (1977) from Längsee sediments. It is similar to type G 128 B (van Geel et al. 1983,1989), but without spines. According, to J.-N. Haas these microfossils belong to the Volvocales and could belong to snow algae (personal communication).

The percentages are based on the pollen sum including trees, shrubs and herbs. Pollen from aquatic plants (*Myriophyllum*, *Potamogeton*, *Sparganium*-type, *Typha*-type), spores of Pteridophyta and mosses, and the NPP are expressed referring to this pollen sum. Only the most abundant types, which are constitutive for the zonation, are presented in the diagrams.

Pollen stratigraphy

The pollen profile of LAE06 showed three major zones and ten sub-zones (Figs. 3, 4a).

Zone P1 (435–390.5 cm)

This zone was characterised by low (max. 30%) arboreal pollen (AP) and high percentages of Poaceae, Cyperaceae and *Artemisia*. The lower half of sub-zone P1/1 (435–409 cm) was determined by very high, but decreasing values of *Pinus*, *Coccus nivalis* (4,000%) and charcoal (200–70%). Type R 70 occurred at approximately 1%. In the upper half of sub-zone P1/1, AP values were <30% dominated by *Pinus* and *Juniperus*. The NAP spectrum was rich and charcoal was decreasing. The abundance of *Coccus*

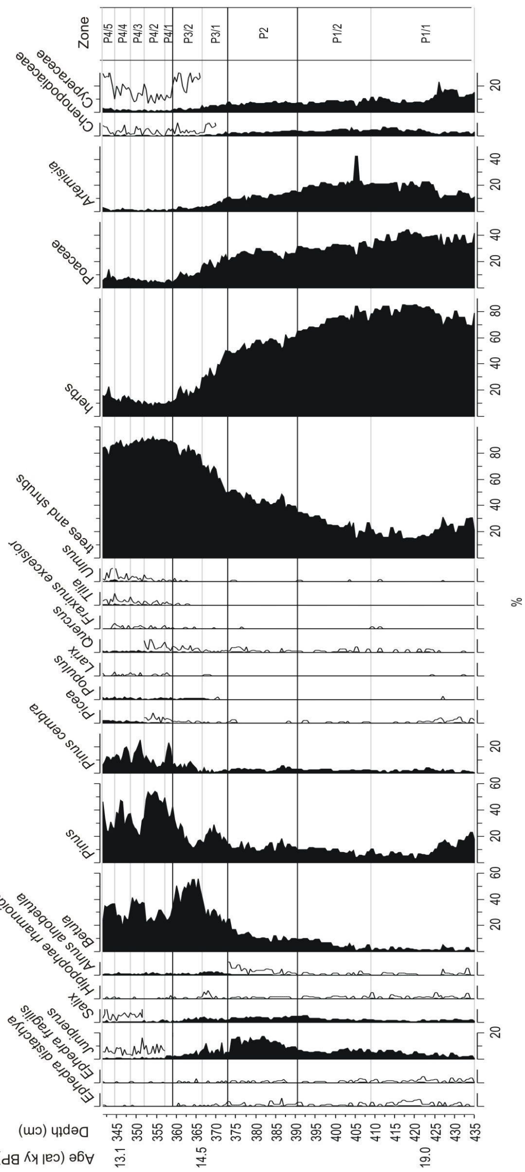

Fig. 3 Pollen percentage abundance diagram of major trees and shrubs and selected herbs of LAE06 showing main zones (*black lines*) and sub-zones

nivalis was low (<500%), but it formed a peak at the transition to sub-zone P1/2 (409–390.5 cm) accompanied by the highest abundance of *Selaginella selaginoides* and the first presence of type G 225. In sub-zone P1/2, the AP values rose to 30% again, due to increasing percentages of mainly *Betula*, *Pinus* and *Juniperus*. Type R 24 started to increase, *Coccus nivalis* and *Selaginella selaginoides* (L.) PB. ex Schrank & Mart. were frequent.

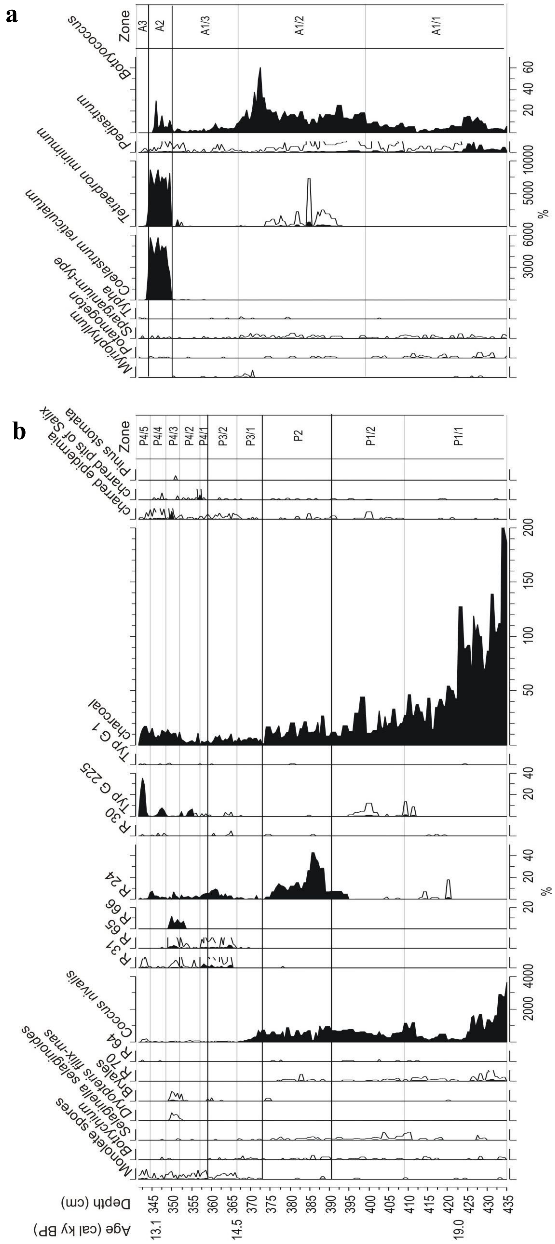

Fig. 4 **a** Percentage abundance diagram of sporophytes, and non-pollen palynomorphs (*NPP*) of LAE06 showing main zones (*black lines*) and sub-zones. **b** Percentage abundance diagram of aquatics (pollen of macrophytes not included in the pollen sum and remnants of algae) of LAE06 showing main zones (*black lines*) and sub-zones

Zone P2 (390.5–373 cm)

Arboreal pollen values rose to approximately 50 % because of increasing percentages of *Betula*, *Pinus* and *Juniperus* (maximum of ± 18%). *Salix* reached values of approximately 5%, *Alnus alnobetula* (Erh.) K. Koch was continuously present (<1%). *Coccus nivalis* (500–1,000%) was still frequent, and type R 24 reached a maximum of approximately 40%.

Zone P3 (373–359 cm)

Arboreal pollen values rose from approximately 50–85%. In sub-zone P3/1 (373–366.5 cm), *Pinus* reached a minor peak at approximately 30%, *Betula* increased to approximately 40%, and the continuous curve of *Populus* started. The abundance of *Coccus nivalis* decreased. In sub-zone P3/2, at a depth of 366.5–359 cm, the first *Betula* peak of approximately 55% occurred, *Pinus cembra* L. exceeded 10%, and the continuous presence of *Quercus* started. The occurrence of type R 31 started in the stratigraphy; R 65 and charred epidermis of Poaceae were present.

Zone P4 (359–341.5 cm)

The AP values exceeded 80%. *Betula*, *Pinus* and *Pinus cembra* fluctuated at high percentages. The presence of Tilia and Ulmus became regular. In sub-zone P4/1 (359–357 cm), *Pinus* dominated at 35–50%, the abundance of *Betula* was relatively low (20–30%) and *Pinus cembra* formed a prominent peak. In sub-zone P4/2 (357–352 cm), *Pinus* reached the first major peak at about 50%. At the transition of sub-zones P4/2 and P4/3 (352–348.5 cm), Bryales, *Dryopteris filix-mas* (L.) Schott and type R 66 appeared. In P4/3, the *Betula* peak was accompanied by a second expansion of *Pinus cembra* and *Picea* exceeded 1%. The presence of Bryales, *Dryopteris filix-mas* and type R 66 (5–10%) became prominent. Sub-zone P4/4 was characterised by a second major peak of *Pinus*. A small decrease in *Betula* was accompanied by a weak increase of NAP. Types R 65 and R 66 disappeared. In sub-zone P4/5 (347–341.5 cm), the increase in *Betula* was accompanied by slightly higher values of NAP (*Artemisia*, Poaceae, Cyperaceae, *Filipendula* and Chenopodiaceae).

Stratigraphy of aquatics

Figure 4b summarises the pollen of aquatic macrophytes not included in the pollen sum and remnants of algae. Three major zones and three sub-zones were differentiated, which are similar to the diatom zones (Fig. 2).

Zone A1 (435–350 cm)

In the lower half of sub-zone A1/1 (435–399 cm) *Pediastrum* (approximately 9%) and *Botryococcus* (approximately 15%) formed distinct peaks. In the upper half, both types decreased. *Potamogeton* (<1%) and *Sparganium* (<1%) showed fluctuating occurrences throughout sub-zone A1/1. In sub-zone A1/2 (399–367 cm), *Tetraedron minimum* (Braun) Hansgirg appeared and formed a minor peak (20–700%). *Botryococcus* showed high abundances with a peak (approximately 60%) towards the upper end. *Sparganium* (<1%) and *Pediastrum* (approximately 1%) were frequent. At the transition between sub-zones A1/2 and A1/3 (367–350 cm), *Myriophyllum* formed a peak (<1%). In sub-zone A1/3 all types decreased.

Zone A2 (350–344 cm)

This zone was dominated by *Coelastrum reticulatum* (Dangeard) Senn (approximately 5,800%) and *Tetraedron minimum* (approximately 8,700%). *Botryococcus* formed a minor peak (approximately 30%). *Sparganium* and *Pediastrum* were present.

Zone A3 (344–341.5 cm)

In zone A3 *Coelastrum reticulatum*, *Tetraedron minimum* and *Botryococcus* disappeared.

Discussion

Dating

Diatom zones D3 and D4 span the time from ca. 13.2–13.0 to ca. 14.9–14.2 cal kyear BP (Table 3). Dating of the lower boundary of this interval is supported by a layer of Neapolitan Yellow Tuff (NYT), which was dated to 14,120 cal year BP in the record of Lago Grande di Monticchio, Italy (Zollitschka and Negendank 1996; Wulf 2000). Based on this date for the NYT and counting of varves, the mass expansion of *Betula* in Längsee was dated to 14,270 cal year BP (Schmidt et al. 2002a). The 2σ range of our ^{14}C date close to the NYT is ca. 14.9 to 14.2 cal kyear BP. The expansion of *Betula* in other records south of the Alps (Lotter et al. 1992a; Vescovi et al. 2007) and the beginning of the Greenland Interstadial 1 (GI-1; ca. 14.7 cal year BP in the GRIP ice core; Walker et al. 1999) have also been dated within this time interval.

The uncertainty of dating in diatom zone D2 can be due to use of unidentified plant material and the presence of several major plateaus in atmospheric ^{14}C during this period (Hughen et al. 2004, 2006; Sarnthein et al. 2007). One inverse date (11,362 ± 76 ^{14}C year BP = ca. 13.4–13.2 cal kyear BP) could be due to sample contamination. The date of 13,015 ± 109 ^{14}C year BP (=ca. 15.9–15.1 cal kyear BP) between diatom zones D1 and D2 lies within a three-step megaplateau of atmospheric ^{14}C (Hughen et al. 2004, 2006; Sarnthein et al. 2007). A bulk sample from a similar stratigraphic position in Längsee was dated to 15,535 ± 160 ^{14}C year BP in a former study (Schmidt et al. 1998). Hence, the beginning of diatom zone D2 is uncertain.

Because of the δ^{13}C value of -16.9‰, the date within the oldest diatom zone D1 of 15,715 ± 88 ^{14}C year BP (=ca. 19.2–18.8 cal kyear BP) should be considered with some caution, as it indicates that the dated inhomogeneous material (Table 3) may have contained aquatic or C_4 plant remnants. Furthermore, deposits from recently deglaciated catchments are particularly exposed to contamination by ^{14}C-deficient carbon from unvegetated bedrock (Sutherland 1980).

Längsee oscillation (diatom zone D1)

Schmidt (1975) found a period of climate amelioration in lake sediments from southern Tyrol (Bolzano), which was indicated by *Pinus* pollen dominance within the so-called Oldest Dryas pollen zone (Firbas 1949, 1954). Because it was older than the pollen stratozone of Bølling, the author called it Pre-Bølling. Schmidt et al. (1998) described a warm climate oscillation in Längsee, which they thought was synchronous with the Pre-Bølling, and which they later on called Längsee oscillation (Schmidt et al. 2001). Despite the dating uncertainty discussed above, our date of ca. 19.2–18.8 cal kyear BP fits well with the warmer sub-section 2b of the Greenland Stadial 2 (GS-2) dated to ca. 19.5–16.9 cal kyear BP (Walker et al. 1999).

In the diatom record, the warming of the Längsee oscillation is shown by the increased abundance of *Cyclotella* species. Planktonic taxa are favoured in lakes with prolonged ice-free growing seasons (Smol and Cumming 2000; Sorvari et al. 2002; Rühland et al. 2003; Schmidt et al. 2004a, b). The average SEWT of the Längsee oscillation is ca. 6°C below the present SEWT in Längsee and ca 2°C below the Längsee late glacial interstadial (=Greenland Interstadial 1, GI 1, Walker et al. 1999). However, temperature maxima during pronounced short-term variations of the Längsee oscillation reached temperature levels of the Längsee late glacial interstadial. The diatom-inferred temperature for the Längsee oscillation fits well with the trends observed in the δ^{18}O values of GRIP (Rasmussen et al. 2006; Andersen et al. 2006).

The accuracy of the diatom-based temperature inference during the Längsee oscillation could be affected by the lacking analogues for *C.* aff. *quadrijuncta* in ALPS06, the occurrence of *C.* aff. *plitvicensis* in only one lake of the calibration data set, and the high percentage of unidentified *Cyclotella* valves. Additionally, the diatom-inferred SEWT might overestimate temperature because of the large number of low-altitude, warmer lakes in the calibration data set and/or the combination of three training sets established during different time periods of the last 15 years.

The absence of a continuous diatom record below the Längsee oscillation in LAE06 can have following reasons: (1) high sediment influx from the catchment caused by sparse vegetation cover and/or increased precipitation, and (2) low temperature. In the first case, this period could correspond with the early phase of the warming during the Längsee oscillation (GS-2b). In the second case it could correspond with the preceding colder sub-section GS-2c of the Greenland Stadial 2.

The higher values of *Pinus* and scarce *Picea* pollen at the bottom of the pollen profile (lower P1/1) could originate from long distance transport. However, Schmidt et al. (1998) suggested that the increase in pollen from cold resistant pine (*Pinus mugo* Turr., *Pinus cembra*) indicates a progression in timberline. Overall, the pollen assemblages are dominated by alpine and steppic elements. Decreasing abundances of *Coccus nivalis* and type R 70, which might be snow algae, could reflect a decrease in snow-rich conditions during the transition between the cold (GS-2c) and the subsequent warmer period (GS-2b = Längsee oscillation). Most probably due to increasing temperature, the algal production of *Botryococcus, Pediastrum,* and diatoms in the lake began. This corresponds with the pollen occurrences of macrophytes (*Myriophyllum, Potamogeton*) and the increase in pollen of Cyperaceae, which together with *Sparganium* may indicate the development of a littoral vegetation zone. The temperature increase probably caused the onset of summer stratification. The absence of meromixis and strong hypolimnetic anoxia, however, is indicated by the presence of ostracods and the fact that calcite is not dissolved (Schmidt et al. 2002a and unpublished data). Hence, nutrient availability from mixing of the water column could have been less important than the availability from catchment sources. This could explain also the dominance of *C. ocellata* within the *Cyclotella* taxa (Schmidt et al. 2002b).

The warming of the Längsee oscillation inferred from the diatom record coincides with a high abundance of pollen from herbs (NAP) that also characterise the following cold period. Possible reasons for these different climatic implications by aquatic and terrestrial organisms could be: (1) The aquatic organisms responded more quickly to warming than the immigrating terrestrial vegetation, which are affected by long generation times, migration lags from refuges and pedogenesis (Monserud and Leemans 1992; Kupfer and Cairns 1996). (2) The local terrestrial vegetation became denser during the Längsee oscillation, thus lowering the relative representation of pollen originating from long distance transport.

Längsee cold period (diatom zone D2)

Diatom dominance changed from planktonic *Cyclotella* taxa to small benthic *Staurosira* taxa indicating climate cooling. *Staurosira* taxa are known to predominate in cold-water lakes with prolonged ice cover and thus reduced growing seasons (Lotter et al. 1999; Lotter and Bigler 2000; Smol and Cumming 2000; Schmidt et al. 2004a, b). Analogous high percentages of *Staurosira* aff. *venter*, which is the most abundant species during the Längsee cold period, were only found in one lake of the calibration data set (Oberhüttensee) at an altitude of 1,863 m a.s.l. The minimum SEWT reconstructed for the Längsee cold period (10.6°C) matches best with the SEWT of 10.4°C measured in Unterer Giglachsee (1,921 m a.s.l.) and Oberhüttensee (Schmidt et al. 2004b). At present, both lakes lie below the timberline. However, the high NAP during the Längsee cold period could indicate conditions comparable to areas at or above timberline. The major difference with respect to modern conditions was, however, that the alpine plants were mixed with steppic elements (*Artemisia*, Chenopodiaceae, *Ephedra* spp.).

The upper part of P1/2 (until P3/1) shows a more or less constant increase in pollen of shrubs and trees. However, this increase is not consistent with the record of aquatic organisms. The SEWT of the Längsee cold period shows distinct short-term fluctuations that had a similar dimension or were even more pronounced than the fluctuations during the Längsee late glacial interstadial (e.g. Gerzensee oscillation). The trend in SEWT indicates a tripartition of the Längsee cold period. A warmer phase, characterised by a slight increase in *Cyclotella* species, separates two temperature decreases, the latter of which is followed by a transition zone towards the Längsee late glacial interstadial. Peaks in *Tetraedron minimum* and type R24 support the tripartition. Since *Tetraedron minimum* was most abundant during the Längsee late glacial interstadial, it could indicate warmer conditions. During the transition zone *Botryococcus* peaked, which is in accordance with the assumed preference for warmer waters (Salgado-Labouriau and Schubert 1977). In our core, however, lowest abundances occurred during warm periods with high percentages of *C. ocellata* during the Längsee oscillation and early Längsee late glacial interstadial. This distribution could indicate that *Botryococcus* is sensitive to increased nutrients and minerogenic influx from the catchment. Minerogenic influx could also explain the decrease in macrophytes during zone A1/3. Assuming that maximum water depth (MD) is related to precipitation, the sample scores along the gradients SEWT (axis 1) and MD (axis 2) indicate that the

Längsee cold period was drier than the Längsee oscillation and the Längsee late glacial interstadial (Fig. 5). Consequently, dryness was not likely to be the limiting factor for the expansion of trees during the Längsee oscillation. During the warmer interphase of the Längsee cold period, *Juniperus* shrubs became more abundant. The subsequent younger cold fluctuations inferred from diatoms, however, are not reflected in the pollen record. Possibly, the dominant *Juniperus* did not respond to the short-term fluctuations in the same way as the aquatic organisms. The difference might be explained by the climatic inhomogeneity of the Längsee cold period and different responses between aquatic and terrestrial organisms.

The trends in the diatom-based temperature inference are consistent with the $\delta\ ^{18}$O trend in the GRIP record, when we assume that the Längsee cold period correlates with the sub-section GS-2a of the Greenland Stadial 2 (Walker et a. 1999). Slight shifts between the SEWT and the GRIP curves could be due to differences in accumulation rates and dating uncertainties. The Längsee cold period could correspond with the cold ice-rafting event Heinrich 1 from the North Atlantic, which started at 17.9 and lasted until 14.7 cal kyear BP (Sarnthein et al. 2007). Ivy-Ochs et al. (2006), based on surface exposure dating (SED), suggested the Gschnitz Stadial of the Alps as the response to Heinrich 1 cooling. Our results also support the assumption of dry conditions during the Gschnitz Stadial (Kerschner et al. 1999). For this stadial a summer air temperature of about 8.5–10°C lower than today was estimated (Ivy-Ochs et al. 2006). When we compare the recent SEWT of 21.7°C (Table 1) in Längsee with the average inferred SEWT of 12.9°C during the Längsee cold period, a similar difference for lake water temperature is evident.

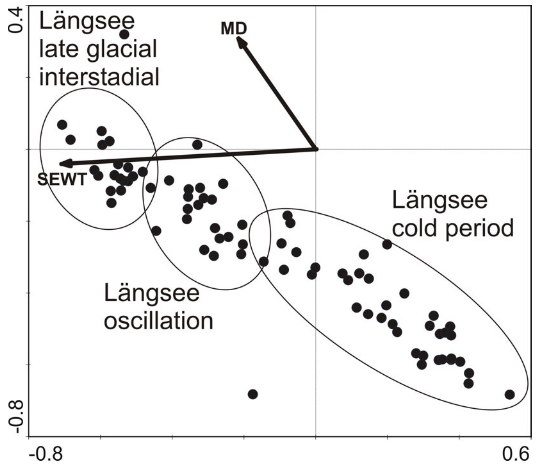

Fig. 5 The core sample scores were added passively to the ordination diagram of species and environmental variables in the calibration data set. Only maximum water depth (*MD*) and summer epilimnetic water temperature (*SEWT*) and the core samples are shown

Längsee late glacial interstadial (diatom zones D3 and D4)

Most of the centric diatoms that were present during the Längsee oscillation became abundant during the Längsee late glacial interstadial, which is equivalent to the Greenland Interstadial 1 (GI 1, Walker et al. 1999), and these diatoms indicate climate warming. This change in the diatom composition corresponded with the expansion of *Betula* (Schmidt et al. 1998, 2002a, b). The presence of *Betula* forests in the catchment of Längsee is supported by many *Betula* macrofossils. The expansion of *Betula* also corresponded with the onset of meromixis. Since meromixis affected nutrient availability, nutrients could have been the major cause of changes in diatom distribution (Schmidt et al. 2002b).

Schmidt et al. (2002a) observed three minor climate fluctuations during the Längsee late glacial interstadial. The oldest one (Lg-FL1) occurred at the transition from the *Betula* to the *Pinus* pollen zone, which was characterised by a strong influx of siliclastics. It was related to the Aegelsee fluctuation dated by Lotter et al. (1992a, b) at the Swiss Plateau at about 12,000 ^{14}C year BP, or ca. 13.9 cal kyear BP. In the pollen record of LAE06, a prominent peak in *P. cembra* occurred at the transition from *Pinus* to *Betula* in P4/1, which may correlate with the climate fluctuation of Lg-FL1. Schmidt et al. (2002a) assumed that nutrient availability from the catchment increased and mixing culminated during this perturbation, resulting in the peak of *C. ocellata*.

The increase in *P. cembra* and *Betula*, together with spores of Bryales (mosses), *Dryopteris filix-mas* and remains of Type R 66 in P4/3, could indicate the climate fluctuation Lg-FL2 described in Schmidt et al. (2002a). However, neither Lg-FL1, nor Lg-FL2 is visible in the SEWT, which showed a temperature plateau during the Bølling/Allerød complex. These differences are also reflected in the abundances of

Coelastrum, *Tetraedron* and *Botryococcus*. The *C. comensis* phase corresponds with the expansion of *Coelastrum reticulatum* and *Tetraedron minimum*. *Coelastrum* are planktonic green algae, which commonly bloom in meso- to eutrophic waters. This ecological preference would, however, contradict the oligo- to mesotrophic conditions inferred from *C. comensis* (Wunsam et al. 1995; Schmidt et al. 1998). According to V. Jankovska (personal communication), *Coelastrum reticulatum* and *Tetraedron minimum* also bloom in oligotrophic waters, when at least short periods of high water temperature occur during the vegetation period in spring and summer. Another possible explanation for the bloom of *Coelastrum reticulatum* and *Tetraedron minimum* could be the establishment of a productive metalimnion when strong meromixis began as indicated by a peak in pigments (Schmidt et al. 2002b). This meromixis occurred during climate warming, as indicated by the pollen stratozone of Allerød (Schmidt et al. 1998) and the increase of pollen from the mixed oak forest.

At the top of the *C comensis* phase, a slight declining trend in SEWT was inferred. It is mainly due to the increase of *S.* aff. *venter*, which occurs in ALPS06 mainly in oligotrophic cold water lakes. Based on its stratigraphic position, this decline correlates with the climatic fluctuation Lg-FL3 described by Schmidt et al. (2002a), who related this fluctuation to the Gerzensee oscillation from Switzerland dated to ca. 11,000 ^{14}C y BP (Lotter et al. 1992a). In the GRIP record, two minor cold climate fluctuations are indicated, of which the sub-stadial GI-1b is the most distinct one. This fluctuation fits well with the SEWT decline during Lg-FL3.

Conclusions

The inferred diatom-based SEWT showed three major sections for the time period between ca. 19 and 13 cal kyear BP. A first section of warming related to the Längsee oscillation that showed an SEWT range between 11.6 and 18.0°C and an average of 15.8°C, which is ca. 6°C colder than today. The following section related to the Längsee cold period showed an SEWT range between 10.6 and 15.9°C and an average of 12.9°C. The Längsee cold period indicated a tri-partition and drier conditions than the previous Längsee oscillation. Both the Längsee oscillation and the Längsee cold period showed strong short-term fluctuations that indicated climatic instability. Another warming period, the Längsee late glacial interstadial, showed higher average temperatures (mean SEWT 17.5°C) compared to the Längsee oscillation. Of the minor climate fluctuations observed during the Längsee late glacial interstadial, the fluctuation that probably relates to the Gerzensee oscillation showed the strongest signal of decline in SEWT. Although in most cases terrestrial plant macrofossils were used for the seven ^{14}C dates, some dating uncertainties remained. The most likely explanation for dating uncertainties is the several ^{14}C plateaus caused by intervals with very low or reversed ^{14}C change with calendar age. Assuming that the lowermost ^{14}C-date is reliable, the summer water temperatures inferred from the diatoms of Längsee are consistent with the trends in the oxygen isotope curve of GRIP. In this case the Längsee oscillation correlates with the warmer sub-section GS-2b of the Greenland Stadial 2. The subsequent Längsee cold period apparently stratigraphically correlates with the colder sub-section GS-2a lasting from 16.9 to 14.7 cal kyear BP, the Heinrich 1 cold event from the Atlantic and partially with the Gschnitz Stadial from the Alps. The Längsee late glacial interstadial is related to the GI-1.

Some discrepancies were observed in the climatic implications of the pollen data, the diatom record, and the record of other aquatic organisms. These discrepancies could have been caused from uncertainties in the diatom-based temperature inference that could result from overestimated species temperature optima due to the structure of the calibration data set. Other potential causes of discrepancy might involve non-analog conditions in both the aquatic and the terrestrial species, such as fossil diatom taxa that are not present in the calibration data set or fossil pollen from plants that are not part of the present vegetation. Differences in response time and sensitiveness between aquatic organisms and terrestrial vegetation might be the cause for different climatic indications shown by aquatic and terrestrial records. The cold-resistant *Juniperus* showed no reaction to short-term climate fluctuations in contrast to aquatic organisms, and might be slow to respond to climatic variation. Discrepancies appear to have been greatest during the times of terrestrial plant immigration.

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Die Bedeutung des Längsees in Kärnten für die Rekonstruktion der Klima- und Seenentwicklung am Ende der letzten Eiszeit

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Abstract

Längsee in Carinthia as a key-site for the reconstruction of climate and lake development during the last glacial termination

Längsee is a small meromictic lake located in the southern pre-alpine lowland (Carinthia). For climatic reconstructions a multi-proxy approach was used (diatoms, ostracods, pollen, geochemistry, mineralogy, varves, tephra). By the use of a diatom-based transfer function for summer epilimnetic water temperatures (SEWT) three major sections were distinguished: (1) a warming period (average SEWT 15.8°C, which is ca. 6°C lower than present), called Längsee oscillation, starting about 18 to 19 kyrs before present (BP). It seems to correlate with the warmer event (GS-2b) indicated by the oxygen isotopes of the so-called Greenland Stadial 2; (2) a following climate deterioration, called Längsee cold period, which could correlate with the youngest cold event GS-2a of the Greenland Stadial GS-2 and the Heinrich I cold event from the Atlantic dated to 17.9 – 14.7 kyrs BP. The SEWT difference of ca. 9°C between inferred and modern Längsee temperatures fits also well with the temperature decline assumed for the Gschnitz stadial of the Alps. Short-term fluctuations (SEWT range between 10.6 and 15.9°C) indicate a tri-partition of this section (two colder phases are separated by a warmer fluctuation); (3) another warming period during the Lateglacial Interstadial (= Greenland Interstadial GI-1). The lower boundary of the initial birch-rich period was dated at Längsee to 14.3 kyrs BP using varves and a tephra layer (Neapolitan Yellow Tuff, NYT, from the Vesuvian area in Italy). Three minor climate fluctuations were observed (mainly by pollen) during this interstadial. The one likely related to the Gerzensee oscillation (Switzerland) or to the sub-stadial GI-1b in the sense of the Greenland isotope event-stratigraphy (both approximately dated to 13 kyrs BP), showed a slight SEWT decline. The Younger Dryas cold period (= Greenland stadial GS-1) between ca. 12.7 – 11.5 kyrs BP appears to have been climatically heterogeneous, indicating a tri-partition in Längsee as well as in several other lake profiles of the Austrian Alps. Climate was also the main trigger of changes in nutrients and meromixis in Längsee.

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Einleitung

Der Längsee (548 m ü. M.) liegt im südöstlichen Alpenvorland Kärntens (Krappfeld nahe St. Veit a. d. Glan) im Randbereich der hochglazialen Moränen des würmzeitlichen Draugletschers (Lichtenberger 1959, Van Husen 1989). Als Würm wird die letzte der vier großen Vereisungen des Eiszeitalters (Pleistozän) in den Alpen bezeichnet. Während des Würm-Hoch oder Pleniglazials (Last Glacial Maximum = LGM) stießen die Gletscher zwischen 23.000 bis 21.000 Jahren vor heute bis in das nördliche und südliche Alpenvorland vor.

Der Längsee weist heute eine sauerstoffarme bis –freie Tiefenzone auf, deren Ausdehnung saisonalen und klimabedingten Schwankungen unterworfen ist (z. B. Honsig-Erlenburg & Schulz 1989, Sampl et al. 2001). Seen mit Teildurchmischung wurden von Findenegg (1935, 1937) als meromiktisch bezeichnet. Löffler (1973, 1975) erkannte, dass der Beginn der Meromixie in Kärntner Seen klimatische Ursachen hat und bis in das Spätglazial zurückreicht. Aufgrund dieser Eigenheiten war der Längsee der erste See Österreichs, der intensiv paläolimnologisch untersucht wurde (Frey 1955, 1956, Löffler 1973, 1975, Harmsworth 1984, Wunsam 1993, Schmidt et al. 1998). Spätere Untersuchungen konzentrierten sich auf den Zeitraum zwischen dem LGM und dem Beginn des Holozäns vor ca. 11.500 Jahren, der auch als “last glacial termination“ bezeichnet wird, bzw. gingen der Frage der komplexen Zusammenhänge zwischen Klima, Meromixie und Nährstoffen in diesem Zeitabschnitt nach (Schmidt et al. 2002a, b). Jüngst wurden quantitative Methoden der Paläolimnologie für die Klimarekonstruktion eingesetzt (Huber et al. 2009). Die Paläolimnologie (Vorzeit-Gewässerforschung) nützt die Ablagerungen (Sedimente) von Seen (Abb. 1) mit den darin enthaltenen Organismenresten für die Rekonstruktion von Klima- und Umweltvariablen.

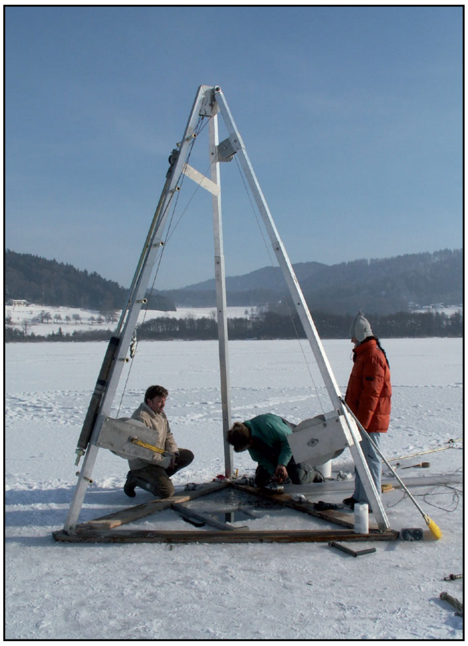

Abb. 1. Bohrung des Sedimentkerns vom Eis des Längsees mit einem Rammkolbenlot (Firma UWITEC, Mondsee) (Foto K. Huber).

Fig. 1. Sediment coring from the frozen Längsee, using a piston sampler (UWITEC, Mondsee) (Photograph K. Huber).

Rekonstruktion der Klima- und Seenentwicklung mit Hilfe multidisziplinärer Methoden

Der Wärmeanstieg nach dem Hochglazial führte zu einem raschen, wahrscheinlich nur einige Jahrhunderte dauernden, Zerfall der alpinen Talgletscher. In dieser Eiszerfallslandschaft bildeten sich nach dem Abtauen sogenannter Toteisreste Seen, wie wahrscheinlich auch der Längsee. Während einer Warmphase nach dem LGM wurden im Längsee fossilführende (z.B. Pollen, Kiesel- und Goldalgen, Muschelkrebse) Sedimente abgelagert. Da im Längsee auf eine Warmphase wieder ein Kälterückschlag folgte, wurde diese Warmphase von Schmidt et al. (2001) als Längsee Oszillation bezeichnet. Zwei Radiokarbondaten (^{14}C) aus dem Bereich der Längsee Oszillation (Schmidt et al. 1998, Huber et al. 2009) ergaben ein Radiokarbonalter (^{14}C) von ca. 15.500 bzw. 15.700 vor heute (bezogen auf 1950), was einem geeichten (= kalibrierten) Alter von ungefähr 18.000 bis 19.000 Kalenderjahren entspricht. Eine Umrechnung der Radiokarbondaten in Kalenderjahre ist notwendig, da der Gehalt der Kohlenstoffisotopen ($^{13/14}C$) in der Atmosphäre Schwankungen unterworfen ist. Hinweise geben sogenannte ^{14}C-Plateaus, d.h. Intervalle mit sehr geringer Veränderung oder sogar inversen ^{14}C-Daten. Die Eichung (in Kalenderjahren) erfolgt u.a. mit ^{14}C-datierten Hölzern und der Auszählung ihrer Jahresringe.

Die Pollenanalyse (Palynologie) bedient sich des in Ablagerungen (Seen, Moore) eingewehten Blütenstaubes (Pollen) von Bäumen, Sträuchern und Kräutern, um die Vegetation früherer Zeiten zu rekonstruieren. In der Längsee Schwankung kam es zu einer Verdichtung der Vegetationsdecke. Dies wird pollenanalytisch aus der Erhöhung der Typenzahl der Kräuter auf Kosten von Beifuß- (*Artemisia*) und Gänsefuß-reichen (Chenopodiaceae) Pollenspektren geschlossen, wie sie für Rohböden und steppenreiche Habitate unter dem kontinentalen Klima der ausklingenden Eiszeit charakteristisch sind (Abb. 2). Im Zuge dieser Warmphase dürfte es auch schon zu einer schwachen Ausbreitung kälteresistenter Gehölze wie Zwergweiden, Wacholder, Zwerg- und Stauchbirken und Föhren (Legföhre, Zirbe) gekommen sein, die entweder südlich der Alpen die letzte Eiszeit überdauert haben, oder von ihren südlichen eiszeitlichen Refugien wie zum Beispiel den Dinariden oder Italien rückgewandert sind (Avigliano et al. 2000, Schmidt et al. 2001). Die Zwerg- und Strauchbirke war in der späten Eiszeit in den Alpen weit verbreitet (siehe u.a. Drescher et al. 2007), beide weisen aber heute hier nur mehr Reliktstandorte auf. Das Vorkommen der Lärche im südlichen Alpenvorland während dieser Zeit ist

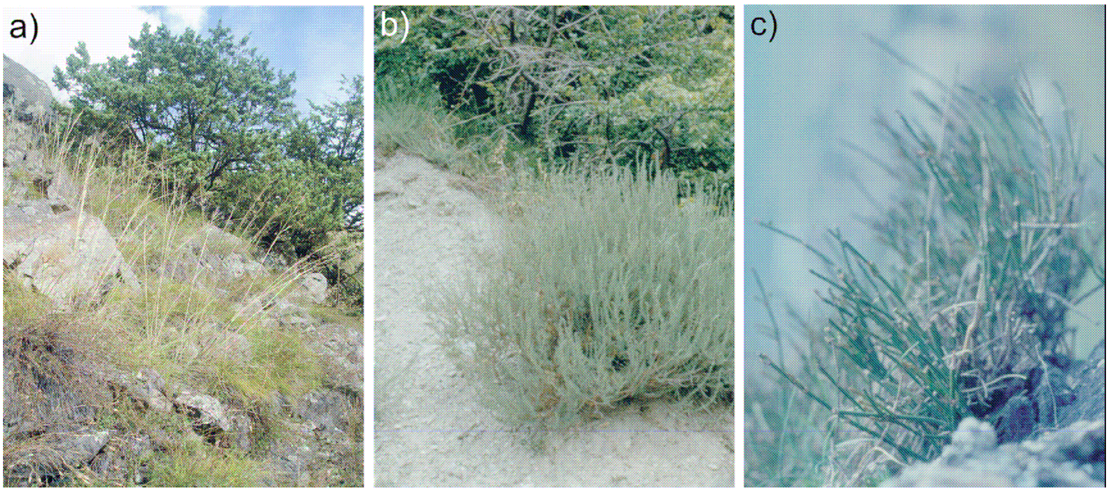

Abb. 2. Pflanzengesellschaften heutiger Steppen und Rohböden, die, nach Pollenanalysen zu schließen, in der späten Eiszeit weit verbreitet waren: (a) Beifuß (Artemisia), Gräser- (u.a. Stipa) und Wacholder-reiche (Juniperus) Felsensteppe (Vinschgau); (b) Kochia prostrata (Gänsefußgewächse, Chenopodiaceae) auf Moränenanriss (Aostatal); (c) Ephedra distachya (Meeträubel), eine zu den Gymnospermen gehörende Pflanze mit Reliktstandorten in den Alpen (z. B. Trento) (Fotos R. Schmidt).

Fig. 2. Association of plants from steppic habitats and initial soils, which, according to pollen analyses, were widespread during late glacial times: (a) Rock steppe rich in *Artemisia*, grasses (e.g. *Stipa*) and *Juniperus* (Vinschgau, South Tyrol, Italy); (b) *Kochia prostrata* (Chenopodiaceae) on glacial moraine (Val d'Aosta, Italy); (c) *Ephedra distachya* (Gymnospermae) on relict sites in the Alps (e.g. Trento, Italy) (Photographs R. Schmidt).

durch Funde von Baumstämmen bei Belluno, Norditalien, belegt (Casadore et al. 1976).

In Pollenprofilen des nördlichen Alpenvorlandes ist diese früher auch als Prä-Bölling (Schmidt 1975) bezeichnete Warmphase der südlichen Alpen (Föhrenvorstoß) nicht oder nur andeutungsweise erkennbar. Dies wird mit der größeren Distanz zu glazialen Gehölzrefugien und mit einem Süd-Nord Temperaturgefälle erklärt (siehe u.a. Fritz 1972, 1978). Im Gegensatz zu den Gehölzen konnten aquatische Organismen (wie die im Längsee nachgewiesenen Kiesel- und Goldalgen, sowie Muschelkrebse, siehe Abb. 3), mit kürzerer Reaktions- und Verbreitungszeit, schneller und intensiver auf das Wärmeangebot reagieren.

Kieselalgen (Diatomeen) aus Seeablagerungen stellen sensible Klimaindikatoren dar. Für die quantitative Rekonstruktion von Klima- und Umweltvariablen müssen diese Bio-Indikatoren jedoch geeicht (= kalibriert) werden. Für die Rekonstruktion der sommerlichen Wassertemperaturen aus den Kieselalgen des Längsees wurde ein Eichdatensatz aus 116 Seen der Alpen und Voralpen verwendet (Wunsam 1993, Wunsam et al. 1995, Schmidt et al. 2004). Mit Hilfe der in der Paläolimnologie gängigen Methode gewichteter Mittel (engl. "weighted averaging, WA", siehe u.a.

Birks 1998) wurde eine sogenannte Transferfunktion für die mittlere epilimnetische Wassertemperatur (SEWT) erstellt und aus den fossilen Diatomeen des Längsees diese Variable berechnet (Huber et al. 2009). Für die Längsee Oszillation wurde ein mittlerer SEWT-Wert von 15,8 °C abgeleitet, was einer Temperaturdifferenz von ungefähr 6° C gegenüber heute entspricht (siehe unten). Unsicherheiten in der Temperaturableitung ergeben sich aus dem modellspezifischen relativ hohen Standardfehler der Vorhersage von 1,8 ° C, sowie aus dem Vorkommen von Arten in der Späteiszeit (siehe u.a. Klee et al. 1993), die heute in den Seen des Eichdatensatzes nicht mehr vorkommen.

Lufttemperatur und Niederschlag beeinflussen das Sauerstoff-Isotopenverhältnis ($\delta^{18}O$) in Gletschereis, Kalkablagerungen und in Kalkschalen von Wasserorganismen (z.B. Muschelkrebse; von Grafenstein et al. 1999, 2000). Damit stellen Sauerstoff-Isotopen empfindliche Klimasensoren dar. Die $\delta^{18}O$-Kurven aus Bohrkernen grönländischer Eiskerne (GRIP und GISP, u.a. Grootes & Stuiver 1993, Andersen et al. 2006, Rasmussen et al. 2006) werden vielfach für großräumige Klimavergleiche in der Nordhemisphäre verwendet. Zieht man die von Walker et al. (1999) erstellte Gliederung des späten Pleistozäns heran, die auf den Isotopenereignissen von GRIP basiert, so dürfte nach den Radiokarbondaten zu schließen die Längsee Oszillation dem wärmeren Intervall (GS-2b) des Grönland Stadials 2 (GS-2) entsprechen (siehe Abbildung 6). Die SEWT-Kurve dieser Erwärmung im Längsee weist größere kurzfristige Schwankungen auf mit einer Schwankungsbreite zwischen 11,6 und 18 °C. Die Temperaturmaxima reichen dabei an die nächste Warmphase, jene des

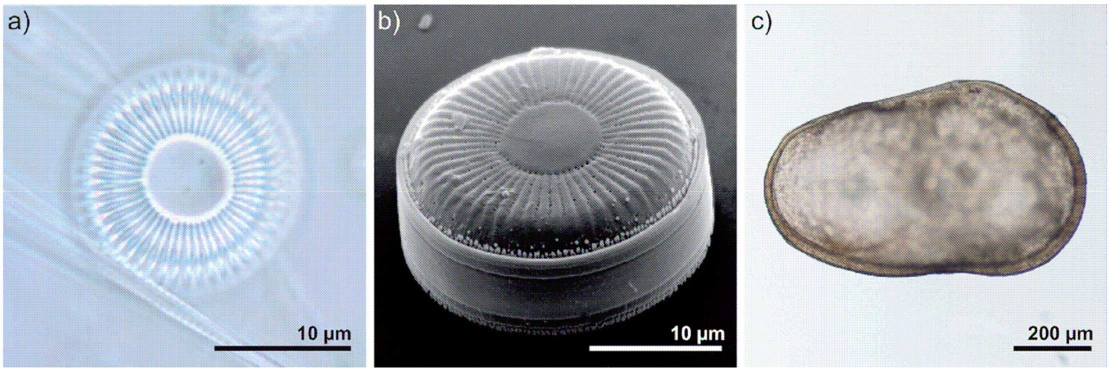

Abb. 3. a, b) Kieselalge Cyclotella plitvicensis im Licht- (a) und Elektronenmikroskop (b) (Fotos C. König/R. Klee) und c) Muschelkrebs Cytherissa lacustris (Foto M. Pichler/D.L. Danielopol) als Beispiele für Bewohner nährstoffarmer und relativ kühler Gewässer, die in der Späteiszeit weiter verbreitet waren als heute.

Fig. 3. a, b) The diatom *Cyclotella plitvicensis* in the light (a) and electron microscope (b) (Photographs C. König/R. Klee), and c) the ostracode *Cytherissa lacustris* (Foto M. Pichler/D.L. Danielopol) as examples of aquatic organisms from waters low in nutrients and temperature, which were wider distributed during late glacial times then at present.

Spätglazialen Interstadials (= Grönland Interstadial 1, GI-1), heran (siehe unten). Die δ^{18}O-Werte von Kalkschalen eines Muschelkrebses (*Cytherissa lacustris,* Abb. 3) aus dem Sedimentkern des Längsees zeigten ebenfalls die klimatische Instabilität während der Erwärmungsphase der Längsee Oszillation (unveröff. Ergebnisse). Untersuchungen an rezenten Populationen zeigen, dass diese Art sehr sensibel auf Temperatur- und Umweltveränderungen reagiert (u.a. Danielopol & Casale 1990).

Die folgende Absenkung der mittleren SEWT um ca. 2,9 °C gegenüber der Längsee Oszillation und des Minimalwerts auf 10,6 °C, lässt auf eine deutliche Klimaverschlechterung schließen. Diese Längsee Kaltperiode wurde von Schmidt et al. (1998, 2001) mit der Pollenzone der Ältesten Dryas (Ia) korreliert. Die sogenannten Dryas-Zeiten, benannt nach der Silberwurz (*Dryas ocotopetala)*, wurden ursprünglich in der Pollenanalyse als Vegetationszonen (Stratozonen) verwendet (Firbas 1954). Während des Kälterückschlags dominieren weiterhin kräuterreiche Pollenspektren. Nach den ^{14}C-Daten könnte dieser Kälterückschlag dem Teilabschnitt GS-2a des Grönland Stadials 2 (GS-2) entsprechen. Kälterückschläge dieser Größenordnung werden auch als Stadiale bezeichnet. Der Kälterückschlag im Längsee könnte auch der als Heinrich Stadial 1 (H1) bezeichneten Kaltphase des Nordatlantik (Bond & Lotti 1995) entsprechen, die zwischen 17.900 und 14.700 vor heute datiert wurde. Während dieser Kaltphase verschob sich die Grenze der nordpolaren Eisdrift nach Süden, was durch verfrachtetes Gestein in den Ablagerungen des Nordatlantiks angezeigt wird („ice rafting events") (Heinrich 1988). In den Alpen ist dieser stadiale Abschnitt durch eine neuerliche deutliche Gletschervorstoßphase nach dem Zerfall der alpinen Talgletscher gekennzeichnet. Der Gletschervorstoß des Gschnitz Stadials – benannt nach dem markanten Moränenwall am Ausgang des Gschnitztales in Tirol – wurde von Ivy-Ochs et al. (2006) der Kaltphase H1 zugeordnet (Kerschner et al. 2008). Die dafür geschätzte Absenkung der Lufttemperatur in diesem Stadial von 8,5 bis 10 °C gegenüber heute, stimmt gut mit der Differenz der Wassertemperatur im Längsee zwischen 12,9 ° C (= $\mathrm{SEWT}_{\mathrm{fossil}}$) und 21,7 °C (= $\mathrm{SEWT}_{\mathrm{rezent}}$, basierend auf Messdaten zwischen 2002 bis 2006, Kärntner Institut für Seenforschung) überein. Der Langzeittrend in den abgeleiteten Wassertemperaturen (Abb. 5) lässt eine angedeutete 3-Teilung erkennen. Zwei kältere Phasen sind durch eine Phase mit höheren Temperaturspitzen getrennt. Versucht man diesen paläolimnologischen Befund auf die Gletscherdynamik umzulegen, so könnten neben dem Gschnitz Stadial nach einer Rückzugsphase noch weitere, derzeit noch nicht genau einzuordnende Gletschervorstöße, untergebracht werden (Ivy-Ochs et al. 2008, Kerschner et al. 2008).

Das folgende spätglaziale Interstadial (= Grönland Interstadial 1) dauerte von ca. 14.700 vor heute bis zum Beginn der Chronozone der Jüngeren Dryas, die mit ca. 12.650 vor heute angesetzt wird. Die Wiederbewaldung am Längsee wurde durch die Ausbreitung von Baumbirken eingeleitet, die relativ raschwüchsig sind und geringe Ansprüche an die Bodenbeschaffenheit stellen. Die Untergrenze dieser charakteristischen interstadialen Birkenausbreitung wurde im Längsee mit Hilfe einer vulkanischen Aschenlage (NYT = Gelber Neapolitanischer Tuff) und der Zählung von Jahreslagen (Warven) auf ca. 14.300 datiert (Schmidt et al. 2002 a). Der NYT konnte aufgrund seiner Gläser und des charakteristischen Chemismus einer Eruption des Vulkanismus um Neapel zugeordnet werden (Orsi et al. 1992). Er wurde im Lago Grande di Monticchio bei Neapel mit 14.120 Kalenderjahren datiert (Wulf et al. 2004) und wurde in den Alpen erstmals im Längsee nachgewiesen. Er ist damit älter als der in Mitteleuropa für das so genannte Alleröd verwendete Leithorizont des Laacher See Tuffs (LST, ca. 12.000 vor heute, van den Bogaard et al. 1985). Diese aus einer vulkanischen Eruption des heutigen Laacher Maares in Deutschland stammende Asche wurde in Österreich bislang nur im Höllerer See nachgewiesen (Klee et al. 1993), einem kleinen Endmoränensee des würmzeitlichen Salzachgletschers nördlich von Salzburg.

Auf den birkenreichen Abschnitt folgt im Längsee ein föhrenreicher Abschnitt, an dem neben der Waldföhre (*Pinus sylvestris*) auch noch die Zirbe (*Pinus cembra*) beteiligt war (Abb. 4).

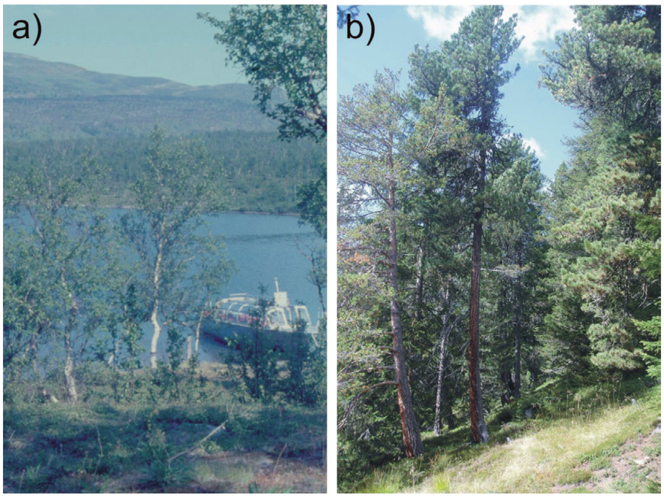

Abb. 4. Vergleichende Vegetationsbilder für das spätglaziale Interstadial des Längsees: (a) Tundrenvegetation mit Baumbirke (Betula alba) und Zwergbirke (Betula nana) als Unterwuchs im Uferbereich eines skandinavischen Sees; (b) Heutige Reliktföhrenwälder mit Waldföhre (Pinus sylvestris) und Verzahnung mit Zirbe (Pinus cembra) nahe der Waldgrenze (Südtirol) (Fotos R. Schmidt).

Fig. 4. Modern vegetation analogs from Scandinavia and the Alps for the late glacial interstadial of Längsee showing birch (*Betula alba*, *B. nana* at the shore of a Scandinavian lake) and pine-dominated (*Pinus sylvestris*, *P. cembra*) forest types close to the timber line in South Tyrol, Italy)(Photographs R. Schmidt).

Innerhalb des spätglazialen Interstadials lassen Verschiebungen in den Pollenanteilen der Föhren, Einschwemmungen silikatischen Materials, sowie Veränderungen in der Zusammensetzung von Algenpigmenten (im Gegensatz zu den Kieselalgen bleiben von den meisten Algen nur die Pigmente in den Ablagerungen erhalten) auf drei kurzfristige Klimaschwankungen schließen. Die Klimaschwankung (Lg-FL1) am Übergang von der Birken- zur Föhrenphase liegt im Bereich des NYT und könnte damit der sogenannten Aegelsee Schwankung (ca. 13.800 v. h.), die jüngste (Lg-FL3) innerhalb der Föhrenphase der Gerzensee Schwankung (ca. 12.800 v. h.) der Schweiz (Lotter et al. 1992, Schwander et al. 2000) entsprechen. Von den drei Fluktuationen des Längsees war die Abkühlung während Lg-FL3 am deutlichsten im SEWT ausgebildet. Dies stimmt sowohl mit dem signifikanten Pollenanstieg der Legföhre als Hinweis einer deutlichen Waldgrenzdepression unter möglicherweise schneereicheren Verhältnissen (Schmidt et al. 2002a), als auch mit dem Isotopensignal des GRIP Eiskerns (Walker et al. 1999) im Falle der Synchronität von Lg-FL3 mit GI-1b überein.

Gegen Ende der Längsee Kaltperiode begannen sich in der Tiefenzone des Längsees die Sauerstoffverhältnisse zu verschlechtern. Dies führte u.a. zu einem Ausfall sauerstoffbedürftiger Organismen in den Beckenablagerungen, wie am Beispiel der Muschelkrebse (Ostracoden) ersichtlich (Löffler 1973, 1975, Schmidt et al. 1998). Die Verschlechterung der Sauerstoffverhältnisse scheint ein graduеller Prozess gewesen zu sein. Mit der Klimaerwärmung des spätglazialen Interstadials trat Meromixie ein (Fehlen einer Vollzirkulation im See und damit verbundener sauerstoffarmer bis –freier Verhältnisse im Tiefenbereich). Dies belegen der Aufbau von Warven (= Jahresschichten) und die im Sediment erhaltenen Farbstoffe (Pigmente) spezifischer Bakterien und Algen (Okenon und Isorenieraten) (Schmidt et al. 2002b). Während Teildurchmischung im älteren Abschnitt des spätglazialen Interstadials noch wahrscheinlich war, dürfte Vollzirkulation des Sees auf die oben erwähnten Klimaschwankungen des spätglazialen Interstadials beschränkt gewesen sein. Die Meromixie erreichte im föhrenreichen Abschnitt ihren Höhepunkt. Dies kann u.a. aus der völligen Auflösung von Kalk (Kalzit) geschlossen werden. Als Ursache der Auflösung wurde eine durch eine stabile Schichtung des Sees bedingte CO_2 Übersättigung des Tiefenwassers angenommen (Schmidt et al. 2002a, b). Dieser Abschnitt klimatisch induzierter strenger Meromixie dürfte mit dem vormals als Allerød bezeichneten Abschnitt synchron sein. Er dürfte niederschlags- (Schnee?) -ärmer als die vorangehende Birkenphase gewesen sein. Letztere deckt sich überwiegend mit dem vormals als Bølling bezeichneten Abschnitt. Beide, benannt nach Lokalitäten Dänemarks, wurden ursprünglich neben der Ältesten Dryas als

Pollen- oder Stratozonen in Mitteleuropa verwendet, die einen bestimmten Vegetationstyp verkörpern. Die beschränkte Verwendbarkeit als Chronozonen wird jedoch u.a. daraus ersichtlich, dass die Birkenausbreitung am Längsee früher erfolgte (Schmidt et al. 2002a) als etwa nördlich der Alpen (Brauer et al. 1999a, Litt et al. 2001), sowie regionale Unterschiede auch noch durch andere Klimaeinflüsse wie zum Beispiel Trockenheit bedingt gewesen sein könnten (Drescher-Schneider et al. 2007).

Algen reagieren allgemein sehr sensibel auf Nährstoffveränderungen, vor allem auf Phosphor. Wunsam & Schmidt (1995) erstellten ein auf Kieselalgen und Phosphormessungen in 86 Seen des Alpenraumes basierendes mathematisches Modell (Transferfunktion) für Gesamtphosphor (TP). Diese Transferfunktion wurde für die Rekonstruktion des Gesamtphosphors im spätglazialen Längsee verwendet. Im birkenreichen Abschnitt (Bølling s.l.) dürfte demnach das Nährstoffangebot durch zumindest temporär höhere Niederschläge und damit Nährstoffeintrag aus dem Einzugsgebiet sowie mögliche Teildurchmischung des Sees größer gewesen sein als im föhrenreichen Abschnitt (Alleröd). In letzterem dürften verminderte Nährstoffeinträge aus dem Einzugsgebiet aufgrund des warm-trockenen Klimas, sowie strenge Meromixie und damit verbundene Phosphoranreicherung („Phosphorfalle“) im Tiefenbereich, zu nährstoffarmen (oligotrophen) Verhältnissen im oberflächennahen Stockwerk des Sees (= Epilimnion) geführt haben (Schmidt et al. 2002 a,b).

Der Klimarückschlag der Jüngeren Dryas, der in der Grönländischen Terminologie (Walker et al. 1999) als Grönland Stadial 1 bezeichnet wird, ist eine weltweit verfolgbare markante klimatische Zäsur am Ende des Spätglazials. Die Chronozone der Jüngeren Dryas (YD) wird gewöhnlich zwischen 11.500 und 12.800 vor heute datiert (Brauer et al. 1999b, Litt et al. 2001). Dieser Klimarückschlag führte in den Alpen zu einer deutlichen Absenkung der Wald- und Schneegrenze und zu neuerlichen Gletschervorstößen (u.a. Kerschner et al. 2000). In Pollenprofilen aus den Alpen ist der Klimarückschlag der Jüngeren Dryas zumeist in einer Erhöhung des Nichtbaumpollen-Anteiles sichtbar. Im Längsee ist dieser dagegen nur geringfügig erhöht, was darauf hindeutet, dass dieser Klimarückschlag zu keiner größeren Lichtung der Wälder (hauptsächlich Waldföhre, *Pinus sylvestris*) in den Tieflagen am südöstlichen Alpenrand führte. Dagegen weist die Erhöhung in den Pollenanteilen von Zirbe und Legföhre in Form von Pollenfernflug sehr wohl auf Verschiebungen im Waldgrenzbereich hin. Zusammen mit Veränderungen in den sedimentologischen Kenngrößen zeichnet sich ein mehrphasiger Verlauf der Jüngeren Dryas ab. Die ältere Phase mit stärkeren Silikatanteilen (Quarz, Schichtsilikate) scheint kühl und

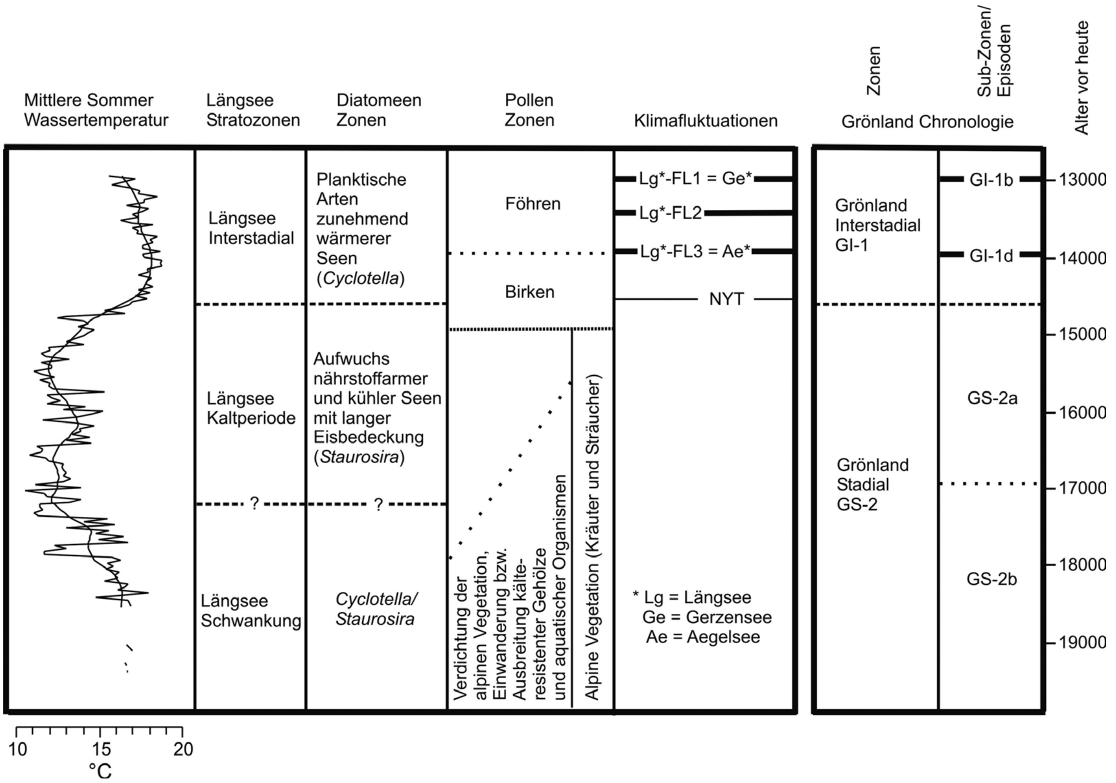

Abb. 5. Zonen-Gliederung des spät-eiszeitlichen Abschnittes zwischen ca. 19.000 und 13.000 vor heute, rekonstruiert mit Hilfe von Kieselalgen (Diatomeen), Pollen, einer Tufflage (NYT), Warvenzählungen und Radiokarbondaten, in Sedimentkernen des Längsees (Schmidt et al. 1998, 2001, 2002, Huber et al 2009). Korrelation der mittleren abgeleiteten Sommer-Wassertemperatur mit der GRIP-Isotopenstratigraphie Grönlands (nach Walker et al. 1999) und mit Klimafluktuationen des spätglazialen Interstadials im Alpenraum.

Fig. 5. Stratigraphy of Längsee in the time-window 19,000 to 13,000 years before present based on diatoms, pollen, a tephra-layer (NYT), varve counting and radiocarbon dating, of sediment cores. The correlation of the inferred mean summer water temperature with the GRIP isotope event-stratigraphy of Greenland (after Walker et al. 1999) and climate fluctuations within the late glacial interstadial in the Alps are added.

niederschlagsreich gewesen zu sein. Diese Klimaverhältnisse dürften im Längsee zu einer Durchmischung (temporäre Auflösung der Meromixie) geführt haben. Nach einem wahrscheinlich wärmeren Abschnitt, der auch als Interphase bezeichnet wurde (Schmidt 1984), folgt ein jüngerer Klimarückschlag. Diese in das Holozän überleitende Phase dürfte kontinentaler als der ältere Klimarückschlag gewesen sein. Diese Phasengliederung des Längsees deckt sich mit der Entwicklung in Seeprofilen aus den Nördlichen Kalkalpen (Salzkammergut) (Schmidt 1984) und mit dem Nachweis von zumeist zwei der Jüngeren Dryas zugerechneten Moränenstaffeln (Kerschner et al. 2000, 2008; Ivy-Ochs et al. 2008).

Schlussfolgerungen

Das Zeitfenster zwischen ca. 19.000 und 12.000 vor heute zeigt im Längsees (Abb. 5) die Entwicklung von hoher klimatischer Instabilität (rasch aufeinanderfolgende Fluktuationen mit Temperaturextremen) zu zunehmender Stabilität. Zwei wärmere Perioden mit stufenweiser Erhöhung der mittleren Sommer-Wassertemperatur (Längsee Oszillation ca. 6 °C und spätglaziales Interstadial ca. 4 °C niedriger als heute) wurden von einer Kälteperiode (= Längsee Kaltperiode) unterbrochen, die wahrscheinlich überregional dem Grönland Stadial 2 bzw. der als Heinrich 1 bezeichneten Kaltphase des Nordatlantiks entspricht. Ähnlich wie die Klimaschwankung der Jüngeren Dryas (= Grönland Stadial 1), die den spätglazialen Abschnitt beendet, scheint auch dieser stadiale Abschnitt durch eine wärmere (trockenere?) Interphase geteilt. Das spätglaziale Interstadial (= Grönland Interstadial 1) zeigt im Längsee drei kurzfristige Kälteschwankungen, die sich auch in den Sauerstoff-Isotopensignalen von Eiskernen Grönlands und zwei Schwankungen in Sedimenten der Alpen wiederfinden, wobei die jüngste Fluktuation (= Gerzensee, Grönland GI-1b?) am deutlichsten ausgeprägt ist. Allgemein lässt das spätglaziale Interstadial am Längsee einen Trend von niederschlags- (Schnee?) reicheren (Bølling) zu warm-trockenen Verhältnissen (Allerød) erkennen.

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Taxonomy, stratigraphy, and palaeoecology of chrysophyte cysts from a Late Glacial sediment core section of Längsee, Austria

by

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Abstract:

Chrysophyte resting stages (cysts) were analysed in a sediment core from Längsee, a small lake in the Carinthian lowland (Austria) with climate-driven meromixis, spanning the Late Glacial Interstadial (= Greenland Interstadial 1, ca. 14.7 to 12.7 ky BP). Of the 32 cyst types occurring at least once with a minimum of > 1 %, six were related to chrysophyte taxa so far. Nine cyst types were described as new to science. Aiming to define ecological preferences, we compared the cyst stratigraphy with pollen and diatom stratigraphies, diatom-inferred total phosphorus (Di-TP) and diatom-inferred mean summer epilimnetic water temperatures (Di-SEWT). Two significant cyst zones corresponded with the two main pollen zones (*Betula* followed by *Pinus*), and a change from meso-eutrophic (dominance of *Cyclotella ocellata*) to oligotrophic conditions (*C. comensis* dominance). Secondary changes in cyst assemblages may have been triggered by climate fluctuations. In sum, we classified three groups of cyst types: (1) cysts related to meso-eutrophic conditions; (2) cysts related to oligotrophic conditions and/or cold water; (3) cysts with unknown ecological preferences.

Introduction

Chrysophytes (classes Chrysophyceae and Synurophyceae) are common microscopic freshwater algae, which often are dominating constituents of lake phytoplankton. Their resting stages (stomatocysts or cysts) are abundant in sediments from alpine and subarctic, pH-neutral, oligotrophic cold-water lakes (Smol & Cumming 2000). Chrysophytes have been shown to be sensitive to pH and alkalinity (Facher & Schmidt 1996; Duff et al. 1997; Pla et al. 2003), conductivity (Duff et al. 1997; Pla & Anderson 2005), trophic status (Rybak 1986; Zeeb et al. 1994, in Duff et al. 1995; Duff & Smol 1995), changes in water temperature (Brown et al. 1997; Lotter et al. 1997), ice cover and lake mixing (Betts-Piper et al. 2004; Kamenik & Schmidt 2005a).

Our study has the following three objectives: (1) to describe the Late Glacial cyst stratigraphy in Längsee (Carinthia, Austria) at a higher time resolution than was done previously; (2) to describe new cyst types found in the sediment core; (3) to relate the ecological preferences of cysts known from literature with climatic and environmental reconstructions that were obtained from other proxies in Längsee. We particularly selected Längsee because (a) its sediments were studied intensively, (b) the lake shows climate-driven meromixis; (c) diatom-bearing sediments date back to early times of deglaciation (e.g., Frey 1955, 1956; Smol 1988; Schmidt et al. 1998, 2002a, b).

Study site:

Längsee (548 m a.s.l.; 46°45’45’’N/14°25’10’’E) is a small (0.75 km^2), 21.4 m deep meromictic lake, situated on carbonaceous bedrock (present pH = 8.4; Schulz 2007) in the Carinthian lowland of Austria. The lake is located in the Würmian Drau glacier retreat area, close to the Würm pleniglacial ice margin (Lichtenberger 1959; van Husen 1976). For more details on location, limnology and morphological characteristics see Schmidt et al. (1998, 2002a, b).

During the Late Glacial Interstadial (= Greenland Interstadial 1 according to the GRIP ice core chronology, Walker et al. 1999), temperatures in the Längsee area increased around 14,300 cal y BP (Schmidt et al. 2002b). The pollen record indicated an initial period rich in birch (Bölling s.l.), which was followed at ca. 13,900 cal y BP by a pine-dominated (*P. mugo, P. cembra, Pinus sylvestris*) period (Schmidt et al. 1998, 2002b). The onset of laminae formation during the birch-rich zone indicated the deterioration of hypolimnetic oxygen conditions (Schmidt et al. 2002b). The diatom assemblage of the Late Glacial Interstadial was dominated by *Cyclotella* taxa. It showed a succession from a *C. ocellata* Pantocsek- dominated period to a phase with *C. comensis* Grunow in Van Heurck dominance. Schmidt et al. (1998, 2002a) interpreted this change as a shift towards lower nutrient availability, when stable meromixis set on during the warm and dry climate conditions of the Alleröd time period. Additional minor climatic fluctuations (Lg-FL1-3), reconstructed from pollen records (Schmidt et al. 2002b), were correlated with the Aegelsee fluctuation (Lg-FL1) and the Gerzensee fluctuation (Lg-FL3), both found in Switzerland (Lotter et al. 1992).

Materials and methods

A sediment core (LAE06) was taken from Längsee in January 2006 with a modified Kullenberg piston sampler (Schultze & Niederreiter 1990) at the deepest point of the lake. After cutting the plastic tubes into halves (for details see Schmidt et al. 2002a), sub-samples were taken at consecutive 0.5 cm intervals from the core section between 344 and 440 cm depth. For dating, we used AMS radiocarbon (^{14}C) dates from terrestrial plant macrofossils (Hajdas et al. 1993), mainly seeds of *Betula*. The sediment was dated at the University of Kiel, Leibniz-Laboratory for Radiometric Dating and Stable Isotope Research. The dates were calibrated using the data set Intcal04 in the CALIB rev 5.01 program (Stuiver & Reimer 1993). For details see Huber et al. (2009).

Chemical cleaning of cyst samples by acid digestion (HCl, H_2O_2) followed Battarbee (1986). Aliquot suspensions were evaporated on glass cover slips, mounted on SEM stubs and sputtered with gold. At least 200 cysts were counted in each sample using a scanning electron microscope (Jeol JSM 35) equipped with an image analyzing system (QUANTEL Crystal) (Kamenik & Schmidt 2005b) at a magnification of 3200x. Specimens of interest were documented by SEM monographs and SEM size measurements (Hitachi S-450). Cysts were classified following the Atlas of Chrysophycean Cysts (Duff et al. 1995; Wilkinson et al. 2001); similar cyst types were flagged by a PEARL prefix. Cysts lacking ornamentation or a collar, having regular or conical pores, were grouped according to size following the diameter ranges given by Kamenik (2001). In the case of uncertain classifications or new cyst types, the respective types were characterised and compared with existing cyst descriptions (Carney & Sandgren 1983; Rybak et al. 1987; Duff & Smol 1991; Facher & Schmidt 1996; van de Vijver & Beyens 1997, 2000; Kamenik 2001; Pla 2001). Cyst descriptive terminology followed the guidelines of the International Statospore Working Group (ISWG; Cronberg & Sandgren 1986) and the Atlas of Chrysophycean Cysts (Duff et al. 1995; Wilkinson et al. 2001). The number of measured specimens used for describing new cyst types ranged from one (L9) to ten (L7).

Cyst counts were converted to percentages. The cyst stratigraphy was plotted using the computer program C2 1.5 (Juggins 2007). For constrained clustering of cyst assemblages along the core (zonation), we used optimal sum of squares partitioning with the program ZONE (Lotter & Juggins 1991). The number of statistically significant zone boundaries was assessed by the broken-stick approach (Bennett 1996). Changes in cyst assemblages were compared with the diatom-inferred mean summer epilimnetic water temperatures (Di-SEWT) (Huber et al. 2009), and the diatom-inferred mean total phoshorus (Di-TP). The latter was based on a calibration data set of 86 alpine and pre-alpine lakes by Wunsam & Schmidt (1995), using weighted averaging with tolerance downweighting and classical deshrinking (Birks et al. 1990). To summarise the overall compositional changes of the chrysophyte and diatom assemblages in LAE06, we used detrended correspondence analysis (DCA), which is a unimodal indirect ordination method (Hill & Gauch 1980).

Results

Cyst characteristics

In total, 62 cyst types were found in LAE06. Of these, 32 occurred with a minimum of > 1 % in at least one sample. Cysts known from literature, including cysts with minor morphological deviations, are listed in Table 1. The following nine cyst types appeared to be new to science:

L1: (Figs 1, 2; 5 size measurements)
Picture-file number: LAE06-344-12, LAE06-348-8
Description: This unornamented, spherical to slightly obovate cyst (diameter 12.7-13.7 µm) has a wide and slightly bended conical collar (basal diameter 5.0-5.4 µm; apical diameter 3.0-3.8 µm; height 2.5-2.8 µm).
Reference: Cyst L1 is similar to PEARL # 41, which was also found in LAE06, having a larger diameter than described by Duff et al. (1995) (see Table 1). L1 was separated from PEARL # 41 found in LAE06 and from PEARL # 41 as described by Duff et al. (1995) by its intermediate diameter and its wider basal collar diameter. In addition the collar appeared to be shorter (broken?), without the distinct hooked apex.

L2: (Fig. 11; 2 size measurements)
Picture-file number: LAE06-354-40
Description: This spherical to oval cyst (diameter 10.1-10.5 µm) is ornamented with randomly oriented short, low ridges (length 1.7-2.3 µm; height 0.5-0.8 µm). The collar is wide and cylindrical, with an obconical to reflexed apex (apical diameter ca. 5.0 µm; basal diameter ca. 3.9 µm; height 1.7-2.3 µm). Inner collar details are unknown.
Reference: Cyst L2 shows similarities with S395 (Pla 2001), which is considerably smaller (diameter 3.6 µm).

L3: (Figs 3, 4; 5 size measurements)
Picture-file number: LAE06-354-20, LAE06-355,5-1
Description: This spherical to sometimes slightly oval cyst (diameter 4.4-4.6 µm) is ornamented with irregularly scattered conula (base diameter 0.2-0.6 µm; height 0.3-0.6 µm), which in some cases reach a length equal to the basal diameter. The collar is conical (apical diameter 1.2-1.5 µm; height 0.2-0.3 µm) with a sloping inner margin. It surrounds a conical to regular pore (diameter ca. 0.4 µm). This cyst was often corroded, especially around the collar.

References: Duff & Smol (1991) described a similar, quite variable cyst (PEARL # 70) with an ovate shape and a cylindrical collar. Duff et al. (1995) pointed out that PEARL # 70 comprises at least two different morphotypes. L3 might be one of them.
L3 also shows similarities with PEARL # 5, which was also found in LAE06 (see Table 1). L3, however, lacks circular depressions on the anterior hemisphere and the conula extend closer towards the collar region than on PEARL # 5.
L3 also resembles No. 50 described by Facher & Schmidt (1996). Unfortunately No. 50 lacks illustrations of the collar region.

L4: (Figs 5, 6; 4 size measurements)
Picture-file number: LAE06-348-2, LAE06-348-6
Description: This spherical cyst (diameter 5.4-6.0 µm) has a more or less regular pattern of conula (base diameter 0.2-0.3 µm; height 0.1-0.3 µm), which sometimes seem to be connected by low ridges. Three to five long, echinate spines (diameter 0.2-0.4 µm; length 3.4-5.0 µm) are located on the posterior hemisphere at irregular distances. The conical collar is low (apical diameter 1.4-1.7 µm; height ca. 0.5 µm), with a rounded apex and a swollen annulus, surrounding a conical pore (diameter 0.5-0.6 µm).
References: Van de Vijver & Beyens (1997) described a similar cyst. Their type (# 10), however, is larger, possesses a smaller pore surrounded by a primary and secondary collar and lacks long, echinate spines.
Duff & Smol (1991) presented a LM image (fig. 155) of an unidentified cyst, which appears to be similar to L4, but is slightly larger and has more spines at the posterior hemisphere.

L5: (Figs 7, 8; 6 size measurements)
Picture-file number: LAE06-355.5-6, LAE06-366-3
Description: This spherical to oblate cyst (diameter 5.8-5.9 µm) is ornamented with long, echinate spines (diameter 0.2-0.4 µm, length 1.0-3.4 µm) on the posterior hemisphere, which may bifurcate. Irregularly scattered and/or circularly arranged conula and verrucae (basal diameter 0.2-0.5 µm; height 0.2-0.5 µm) are located on the anterior hemisphere, or slightly subequatorial. The region around the collar is always unornamented. The conical collar (apical diameter 1.5-1.8 µm; height ca. 0.6 µm) has a rounded apex, a swollen annulus and surrounds a regular pore (diameter 0.5-0.7 µm).
Reference: This cyst type is similar to cyst 73, described by van de Vijver & Beyens (2000). Their cyst is, however, larger, has an obconical collar and lacks ornamentation of the anterior hemisphere. Spines on the posterior hemisphere may have hooked apices.
L5 also resembles S381, described by Pla (2001), which is slightly larger and has an obconical collar that shows slightly longitudinal striae at the abrupt base.

L6: (Fig. 12; 2 size measurements)
Picture-file number: LAE06-344-29
Description: This spherical cyst (diameter 8.2-8.5 µm) is covered with low, rounded ridges (length 1.3-4.2 µm, height 0.2-0.3 µm), which tend to be longitudinally oriented and start at the collar base. The conical to slightly obconical collar (apical diameter 2.1-2.2 µm) surrounds a deep, regular pore (diameter ca. 1.0 µm).
Reference: Cyst L6 looks like PEARL # 111. PEARL # 111 was also found in LAE06, having a wider size range than described by Duff et al. (1995) (see Table 1).

L6 had a smaller diameter than PEARL # 111 morphotypes found in LAE06. Furthermore, PEARL # 111 differed from L6 by having a cylindrical collar with a sloping inner margin.
L6 also compares with cyst No. 86 described by Facher & Schmidt (1996). The latter, however, is larger and has a cylindrical collar with a flattened, obconical or reflexed apex.
L6 also resembles a corroded form of S378, described by Pla (2001), which is smaller than L6.

L7: (Figs 9, 10; 10 size measurements)
Picture-file number: LAE06-355.5-3, LAE06-354-21
Description: This spherical to slightly obovate cyst (diameter 6.8-7.4 µm) is ornamented with ridges of variable length (length 2.3-8.2 µm; height 0.1-0.7 µm) which are arranged more or less latitudinally. The ridges are located mainly on the posterior hemisphere or sometimes slightly pre-equatorially. The collar is conical (apical diameter 1.2-1.5 µm; height 0.2-0.3 µm), often with a strutted base. It has a sloping inner margin and surrounds a conical pore (diameter 0.6-0.7 µm).
Reference: L7 could not be assigned to cysts known from literature. It probably represents a new cyst type.

L8: (Fig. 13; 2 size measurements)
Picture-file number: LAE06-354-31
Description: This large, spherical cyst (16.9-18.4 µm) has a coarsely textured surface. Ridges (length 5.5-17.0 µm; height 0.5-1.7 µm), which start at some distance from the collar base, are oriented more or less longitudinally. The collar, which was often corroded, is cylindrical with a conical base (basal diameter ca. 5.0 µm; apical diameter ca. 2.7 µm; height up to 1.7 µm). Pore and inner collar details are unknown.
Reference: This cyst is similar to PEARL # 173. It is slightly smaller, with a narrower collar base. The SEM image presented by Duff et al. (1995) shows a smooth cyst surface in between the ridges, whereas L8 is coarsely textured.

L9: (Fig. 14; 1 size measurement)
Picture-file number: LAE06-354-37
Description: This almost spherical (diameter ca. 9.3 µm, without the circulus) cyst type is ornamented with an acute, undulating incomplete circulus (height 1.1-1.7 µm). One specimen showed an additional short ridge (length ca. 4.1 µm), in an approx. right angle to the circulus. The collar is cylindrical with a conical base (apex diameter, height). Inner collar details are unknown.
References: This cyst is similar to No. 93 in Facher & Schmidt (1996) and S357 in Pla (2001). L9 contrasts both cyst types by the position of the circulum, which is not in the same plane as the polar axis, and by the additional short ridge.

Stratigraphy

According to Optima Partitioning and the broken stick model, the chrysophyte cyst stratigraphy showed one statistically significant zone boundary at 352.5 cm, separating zones 1 and 2 (Fig. 15):

Zone 1 (366.5-352.5 cm):
Within this zone unornamented cysts prevailed (49-83 %). Sub-zone 1/1 was dominated by cysts without ornamentation and a conical pore (> 8.8 µm) (6-40 %) and PEARL # 116 *forma* B (9-38 %). Cysts without ornamentation and a regular pore (5.3-8.8 µm), PEARL # 41, PEARL # 241, PEARL # 223, PEARL # 111 and PEARL # 171 were frequent. In sub-zone 1/2, cysts without ornamentation and a conical pore (> 8.8 µm) and PEARL # 116 *forma* B declined markedly, whereas PEARL # 41, PEARL # 31, PEARL # 179 and PEARL # 171 increased in abundance. This transition at 365.5 cm, delineating the sub-zones 1/1 and 1/2 (Fig. 15), did not affect unornamented cysts having a regular pore (5.3-8.8 µm), PEARL # 111 and PEARL # 223. Within sub-zone 1/2 a single occurrence of cyst L9 (2 %) was observed.

Zone 2 (352.5-344.0 cm):
In this zone unornamented cysts reached their highest abundance (78-97 %). Those with a conical pore (> 8.8 µm) prevailed (25-60 %). L1 increased in abundance (up to 10 %) at the expense of PEARL # 41. The abundance of PEARL # 171 decreased clearly compared to zone 1. Unornamented cysts having a regular pore (> 8.8 µm) and PEARL # 234 became more common. L2 (1-4 %) and PEARL # 159 *forma* B (1-3 %) occurred only in the upper part of zone 2, where PEARL # 49 formed a peak (max. 17 %) and PEARL # 116 *forma* B disappeared.

Discussion

The chrysophyte cyst assemblages in the Längsee sediment core (LAE06) are dominated by cysts that might have been produced by more than one species. Unornamented cysts lacking a collar and having a regular pore are usually combined in collective categories (e.g., Duff et al. 1995; Pla 2001). In Längsee, unornamented cysts lacking a collar and having a conical pore probably represent several species, too. Nevertheless, the majority of cysts in LAE06 could be assigned to types known from literature (Table 1). So far, only six of these types were linked to the species that produce them (e.g. Duff et al. 1995; Wilkinson et al. 2001), and only little is known about their ecology. Hence, we compared our cyst stratigraphy with past environmental conditions inferred from diatoms, pollen, mineralogy and geochemistry (Schmidt et al. 1998, 2002a, b; Huber et al. 2009).

Cyst zone 1 is almost identical with the diatom zone dominated by *Cyclotella ocellata* (Fig. 16). This species thrives in meso-eutrophic lakes according to large European diatom data sets (ALPTROPH: Wunsam & Schmidt 1995; EDDI: Juggins 2001). It appears to dominate over other diatoms when nutrient increases coincide with elevated minerogenic matter (Teubner 1995). In Längsee, increased nutrient concentrations in zone 1 might have originated from lake mixing and/or catchment erosion. Schmidt et al. (2002b) assumed that variable climate conditions caused facultative meromixis, i.e. alternation between periods with stable stratification and mixing. Pigments produced by sulphur bacteria supported this hypothesis.
PEARL # 41 is produced by the cosmopolitan species *Dinobryon cylindricum* O.E. Imhof (Donaldson & Stein 1984; Duff et al. 1995). This cyst was found in cold, oligotrophic as well as nutrient-enriched waters (Rybak 1986; Rybak et al. 1987; Eloranta 1989; Siver 1995). In LAE06, PEARL # 41 is more or less restricted to zone 1, potentially indicating a preference for increased nutrient concentrations. It might

also be favoured by rapid changes in lake-water mixing, and short-term fluctuations in nutrient availability that depend on mixing. *Dinobryon* is mixotrophic (Bird & Kalff 1987); *D. cylindricum* was common in meromictic lakes of southwest Greenland, rich in purple sulphur bacteria (Pla & Anderson 2005).

Similar to PEARL # 41, PEARL # 128 *forma* D (Wilkinson et al. 2001) was found on a purple-coloured layer at the sediment-water interface. It may use the mat of sulphur bacteria as substratum (Betts-Piper et al. 2004). PEARL # 128 *forma* B, which was most frequent in cyst zone 1, might favour similar environments. Wilkinson (1997, in Wilkinson et al. 2001) found the abundance of PEARL # 128 *forma* B to be positively correlated with increased total phosphorus.

PEARL # 171 may be produced by a eutrophic taxon (Rybak et al. 1991). The appearance of this cyst type mainly in cyst zone 1 supports the previously defined ecological preference.

PEARL # 31 shows a wide tolerance for trophic status (Duff & Smol 1988, 1989; Zeeb et al. 1990; Duff 1994, in Duff et al. 1995). It increased in sub-zone 1/2 which is characterised by *Asterionella formosa* Hassall and *Cyclotella* aff. *cyclopuncta* Håkansson & J.R. Carter. These diatoms indicate a transitional trophic stage between the *C. ocellata* and the *C. comensis* dominated periods. Its distribution in LAE06 suggests a preference for mesotrophic conditions.

PEARL # 179 is probably produced by *Chrysidiastrum catenatum* (Lauterborn) Lauterborn (Sandgren 1983, in Duff et al. 1995). Duff (1994, in Duff et al. 1995) suggested that this taxon has a low tolerance for eutrophication. In LAE06, however, it occurred mainly during sub-zone 1/2, suggesting a preference for mesotrophic conditions.

Cyst zone 2 mainly corresponds with the *Cyclotella comensis* diatom zone (Fig. 16). This species is predominantly found in oligotrophic lakes (ALPTROPH: Wunsam & Schmidt 1995; EDDI: Juggins 2001). In Längsee, it is associated with other diatoms related to oligotrophy (e.g. *C.* aff. *plitvicensis* Hustedt) (Huber et al. 2009). Oligotrophy was likely caused by strong meromixis and phosphorus trapping in the hypolimnion during the warm and dry climate conditions of the Alleröd (Schmidt et al. 2002b).

Unornamented cysts, which often dominate in clear, oligotrophic lakes (Stewart et al. 2000; Pla 2001; Betts-Piper et al. 2004; Pla & Anderson 2005), culminated in zone 2.

PEARL # 49 follows this trend. This cyst is probably produced by *Chrysosphaerella longispina* Lauterborn emend. K.H. Nicholls (Sandgren 1989). It is widely distributed, and up to now, it showed no clear ecological preferences (Rybak et al. 1991; Zeeb & Smol 1993a, in Duff et al. 1995). Its distribution in LAE06 suggests a preference for oligotrophic conditions.

PEARL # 156, for which no ecological information was available up to now (Duff et al. 1995), was restricted to cyst zone 2. Its occurrence in this zone might indicate a preference for oligotrophic conditions.

PEARL # 41 and L1 show a similar morphology (see above). In zone 2, cyst L1 increased at the expense of PEARL # 41. L1 might represent the oligotrophic ecotype of PEARL # 41. Both morphotypes are probably produced by the same taxon.

According to their stratigraphic position, the following cyst types may have been affected by low temperature during Late Glacial climate fluctuations, particularly during the most pronounced cooling of Lg-FL3, which was related to Gerzensee (Fig. 16).

PEARL # 234 occured mainly during this cooling period. It is probably produced by several species of *Paraphysomonas* (Duff et al. 1995).
PEARL # 116 was often associated with oligotrophic lakes (Duff 1994, in Wilkinson et al. 2001). Palaeolimnological data suggest, however, that it is an indicator of meso- to eutrophic conditions (Rybak et al. 1987; Zeeb et al. 1990; Zeeb & Smol 1993b, in Duff et al. 1995). In LAE06, PEARL # 116 *forma* B showed no clear preferences. Brown (1996, in Wilkinson et al. 2001) estimated a surface-water temperature tolerance from 17.4 to 19.5 °C for this cyst type, which ranges slightly above the average Di-SEWT in LAE06 (Fig. 16; Huber et al. 2009). When water temperature declined during Lg-FL3, PEARL # 116 *forma* B disappeared (see Fig. 16).
L2 might be produced by a cold-water taxon, since it is restricted to the samples 345.5-344.0 cm in LAE06. PEARL # 159 *forma* B occurred in the same sediment depth of LAE06. However, it seems to be a generalist regarding lake trophic status (Rybak 1986, Zeeb & Smol 1993b, in Duff et al. 1995).
PEARL # 31 is probably produced by a cold-water tolerant taxon (Adam 1980, in Duff et al. 1995; Duff & Smol 1988,1989). It could have been more tolerant against cold waters than PEARL # 179, according to their stratigraphic distribution in LAE06 and the position of Lg-FL1 and Lg-FL2.

The following cysts were distinguished in both zones of core LAE06, showing no clear preference, or were restricted to individual samples: PEARL # 5 *forma* A, PEARL # 111 (produced by *Spiniferomonas trioralis* E. Takahashi; Skogstad 1986, in Duff et al. 1995), PEARL # 112 (probably produced by *Ochromonas globosa* Skuja; Nygaard 1977, in Duff et al. 1995), PEARL # 130 (produced by *Chrysococcus furcatus* Dolgoff; Nicholls 1981, in Duff et al. 1995), PEARL # 180 (produced by *Spiniferomonas bourrellyi* E. Takahashi; Skogstad & Reymond 1989, in Duff et al. 1995), PEARL # 223, PEARL # 241, L3, L4, L5, L6, L7, L8 and L9.

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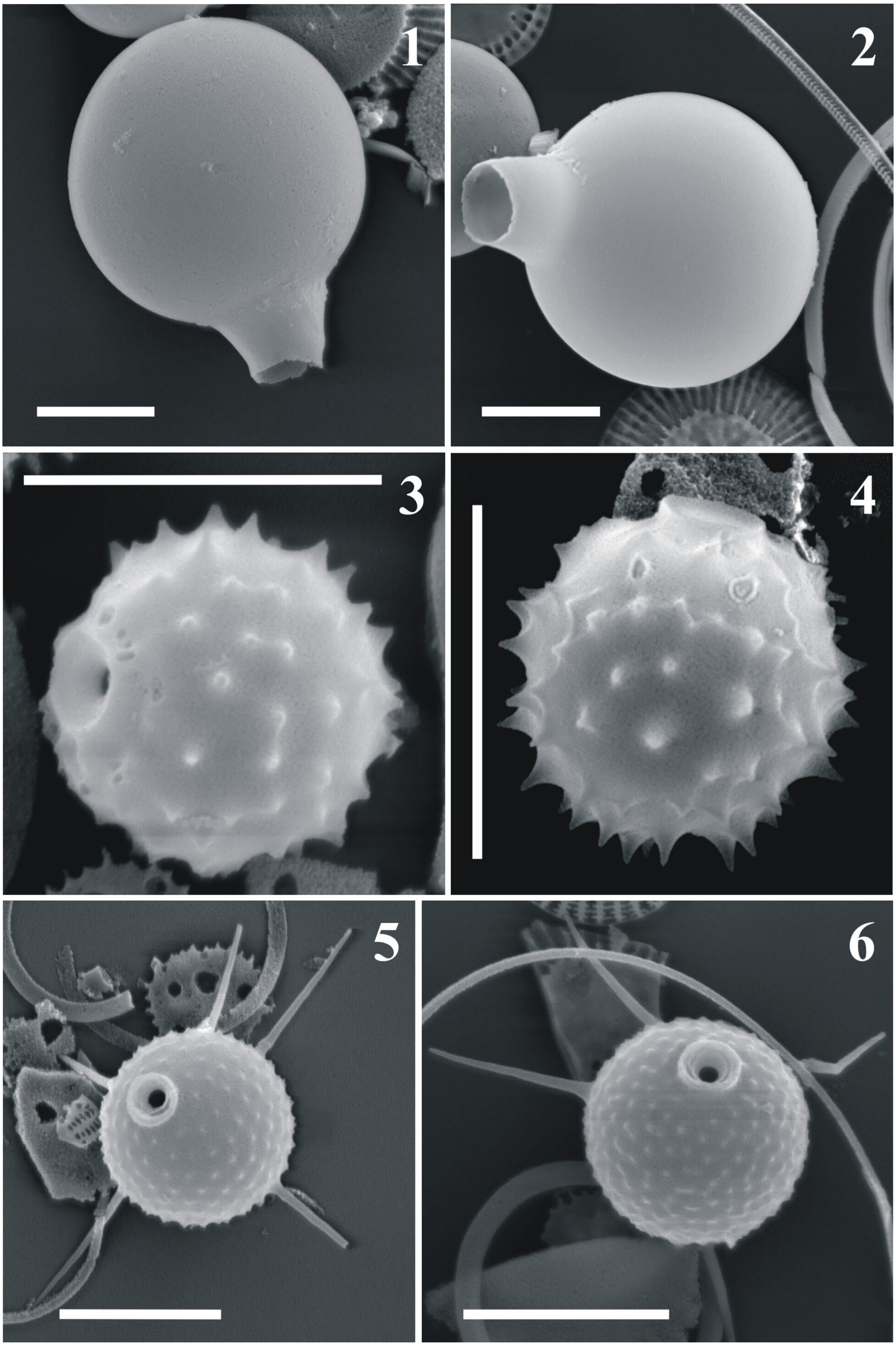
Tables

Table 1: Cyst types found in Längsee sediments that were described by Duff et al. (1995) or Wilkinson et al. (2001). These types were flagged by a PEARL prefix.

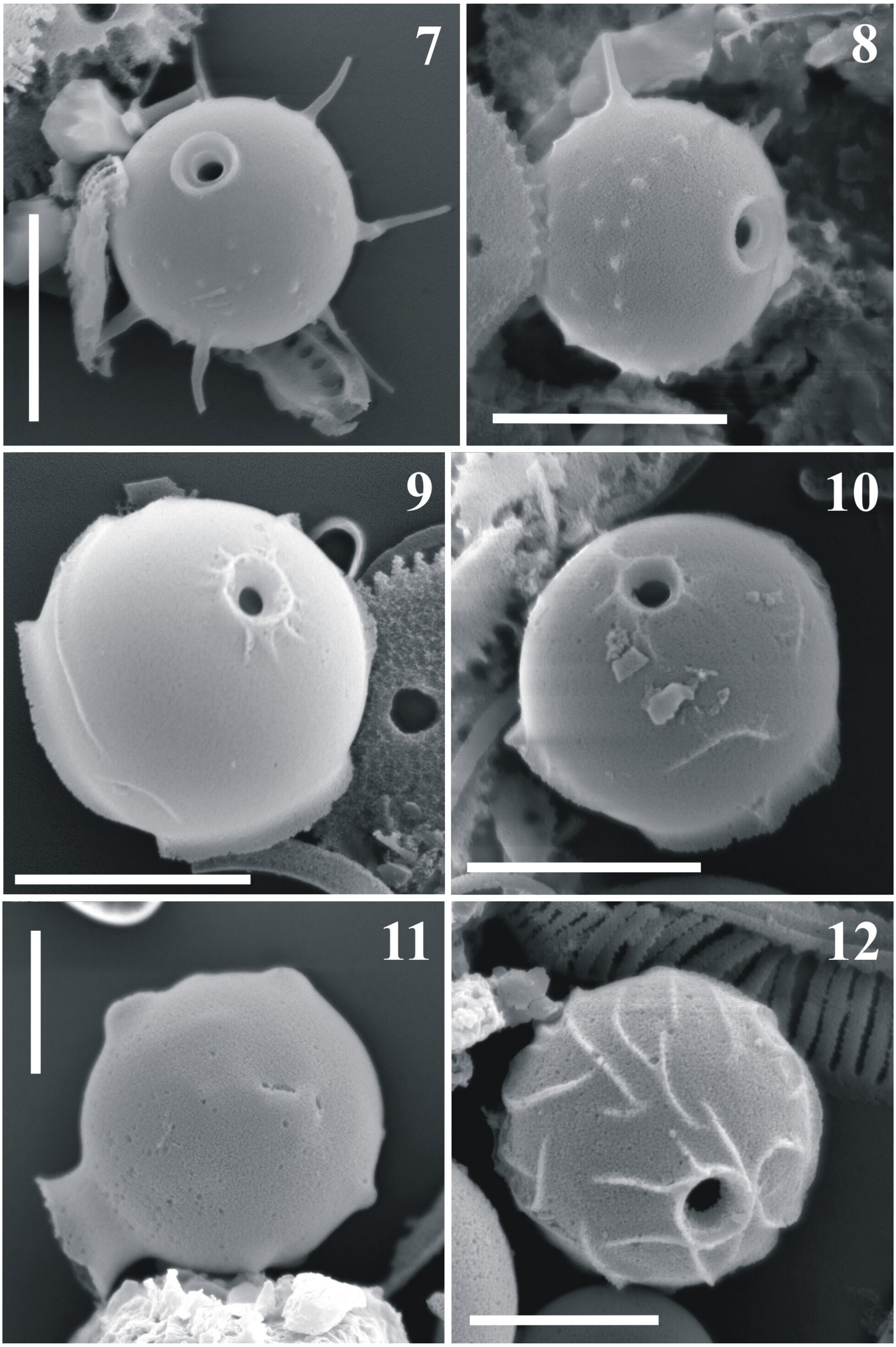
Corresponding numbering	Comments
PEARL # 5 *forma* A	
PEARL # 31	
PEARL # 41	The type in LAE06 has a larger diameter (13.5-14.2 µm) than # 41; the same size was observed by Facher & Schmidt (1995) (see cyst No. 13), Rybak et al. (1987) (see cyst 3) and Carney & Sandgren (1983) (see *Cysta curvicollis*).
PEARL # 49	Some cysts in LAE06 have a larger diameter (max. 10.9 µm) than # 49.
PEARL # 111	Several cysts in LAE06 have a larger diameter (8.4 to 11.1 µm) than # 111.
PEARL # 112	Several of the cysts in LAE06 have a smaller diameter (11.4-15.7 µm) than # 112.
PEARL # 116 *forma* B	Some cysts in LAE06 have a slightly obconical collar; the same collar was observed by Pla (2001) (see cyst S161).
PEARL # 128 *forma* B	
PEARL # 130	No striae or struts at the outer basal margin of the collar and no twisted appearance of the single, echinate spine could be observed on cysts in LAE06; the pore was smaller in diameter (ca. 0.7 µm – compare with cyst S130 in Pla 2001).
PEARL # 156	
PEARL # 159 *forma* B	
PEARL # 171	
PEARL # 179	
PEARL # 180	The reticulum of the cysts in LAE06 is lower and less regular than on # 180.
PEARL # 223	The cysts in LAE06 have a larger diameter (3.8-4.6 µm) than # 223; the same size was observed by Facher & Schmidt (1996) (see cyst No. 81).
PEARL # 234	Several cysts in LAE06 have a larger diameter (7.6-8.2 µm) than # 234.
PEARL # 241	Several cysts in LAE06 have a larger diameter (8.1-9.8 µm) than # 241 and the surface is always smooth; a larger diameter was also observed by Pla (2001) (see cyst S112).

Figures

Figs 1-6. Scale bars = 5 µm (SEM); Figs 1 & 2: L1, Figs 3 & 4: L3, Figs 5 & 6: L4.



Figs 7-12. Scale bars = 5 µm (SEM); Figs 7 & 8: L5, Fig. 9 & 10: L7, Fig. 11: L2, Fig. 12: L6.



Figs 13-14. Scale bars = 5 µm (SEM); Fig. 13: L8, Fig. 14: L9.

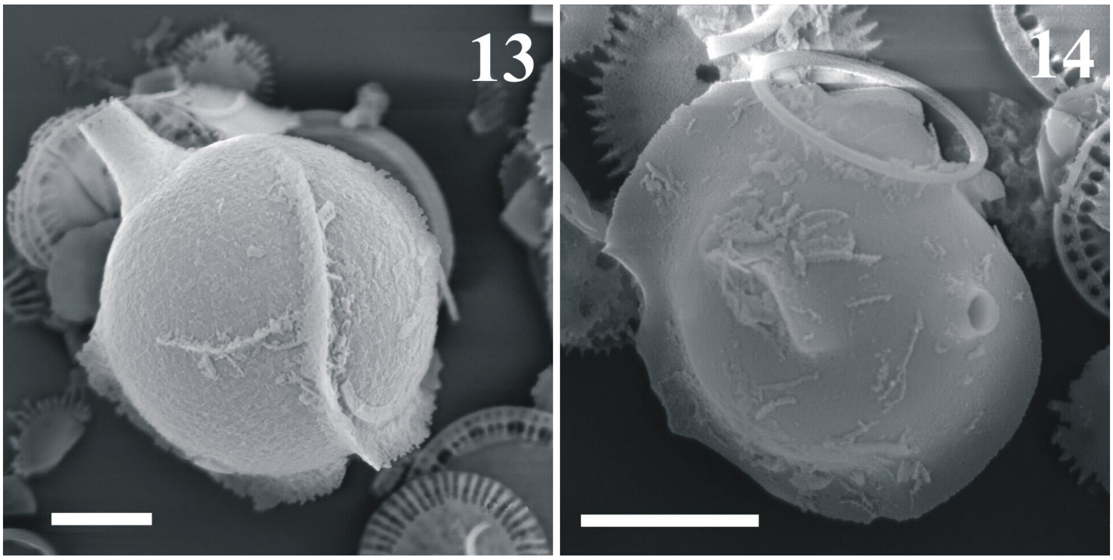
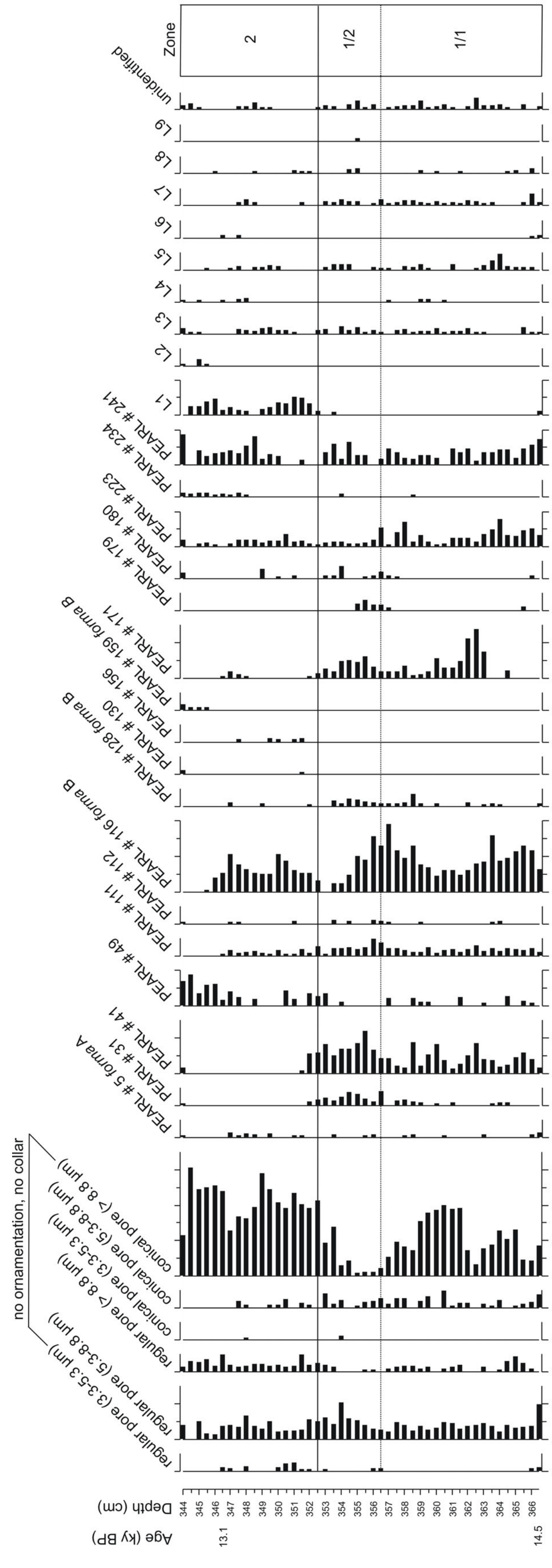


Fig. 15: Stratigraphy of selected cyst types (%) in LAE06, and cyst zones.



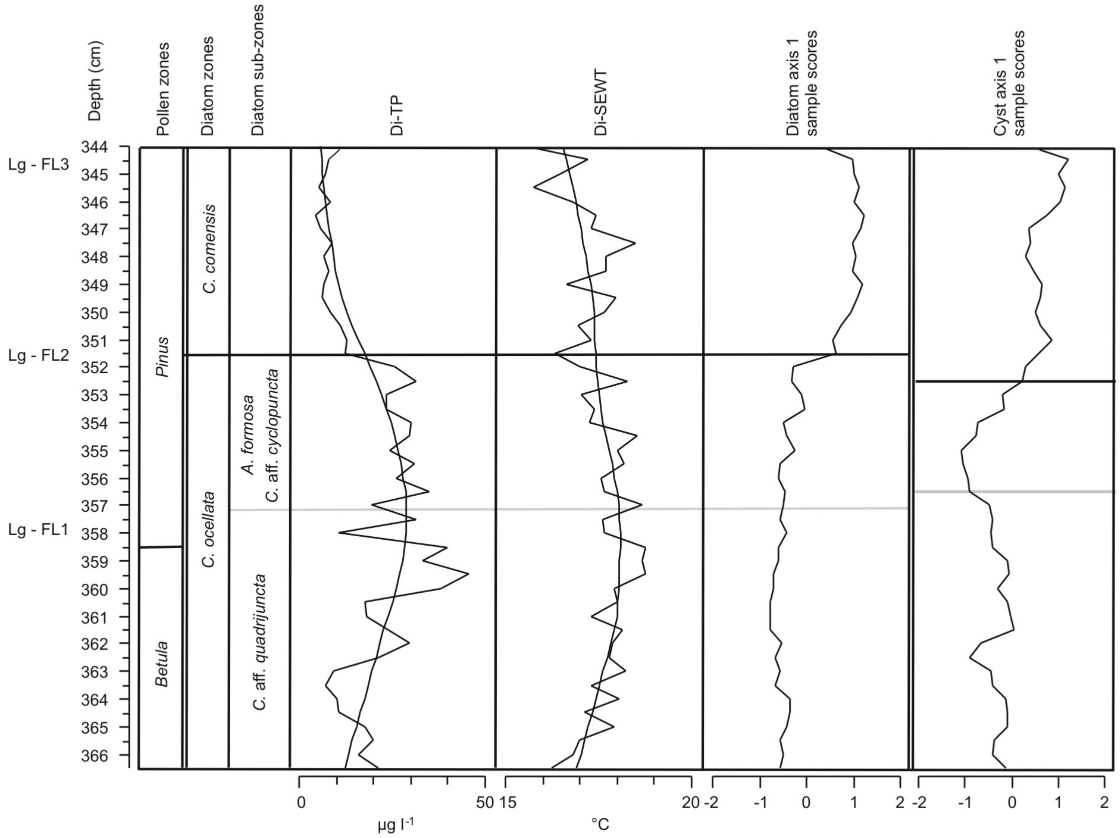


Fig. 16: Major pollen and diatom zones of LAE06; diatom-inferred total phosphorus (Di-TP) and diatom-inferred summer epilimnetic water temperature (= Di-SEWT, Huber et al. 2009); diatom and cyst DCA axis 1 sample scores; major zone (black) and sub-zone (grey) boundaries; short-term climatic fluctuations (Lg-FL1-3, Schmidt et al. 2002a).

Climate change during the last glacial termination in the south-eastern Alps inferred from a high resolution multi-proxy sediment stratigraphy

In prep.

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Abstract

A sediment core section from Jeserzersee spanning the time from approximately 19 to 15 cal ky BP was analysed using a multi-proxy approach (diatoms, pollen, mineralogy and grain-size). The small lake is located in the Carinthian lowland (Austria), about 32 km away from the Würmian pleniglacial ice-margin of the former Drau glacier. A warming period of Pre-Bølling time (> 17 cal ky BP) inferred from the multi-proxy data, locally called Jeserzer-See-Schwankung, is likely to correlate with another warm oscillation described from the same area (Längsee oscillation) and, on a northern hemispheric scale, with the warmer sub-section GS-2b of the Greenland Stadial 2 (GS-2). It was followed by a climate deterioration, which was related to the pollen zone of the Oldest Dryas, to the cold ice-rafting event Heinrich 1 of the North Atlantic, and to the colder sub-section GS-2a of the Greenland Stadial 2. This period is, however, climatically heterogenous: In the beginning of the period the diatom-inferred summer epilimnetic water temperature (SEWT) and the mineralogy indicated a tri-partite older cold phase with a SEWT decline of ca. 10°C against present, which was related to the Gschnitz stadial of the Alps. Differences in grain size and mineralogy within this older cold phase indicated a shift from wetter to drier climate conditions. The older cold phase was separated by a warmer phase from a younger less prominent cold phase, which, however, is not reflected in the pollen record. This might be due to the fact that aquatic organisms are more sensitive to climatic change than terrestrial vegetation, which at the time was dominated by the cold-resistant *Juniperus*. The younger cold phase may possibly correlate with the Clavadel/Senders stadial of the Alps. A transitional phase to the Late Glacial Interstadial (= Greenland Interstadial 1) starting at about 16 cal ky BP indicated increasing temperature and precipitation.

1. Introduction

The interval between the Last Glacial Maximum (LGM) (= Alpine Würm Pleniglacial) and the Late Glacial Interstadial (LGI) covers the time window from approximately 21.5 to 14.5 cal kyr before present (BP) (e.g. Preusser 2004). For the Alps, Penck and Brückner (1909) established the fundamental concept of a stepwise succession of glacier retreat and re-advance. For the "Alpine Lateglacial", they described the stadials Bühl, Steinach, Gschnitz, Daun and Egesen. Recently attempts have been made to establish a chronostratigraphy for these classical Alpine stadials and to put them into the frame of northern hemispheric climate (van Husen 2004; Preusser 2004; Kerschner 2005; Ivy-Ochs et al. 2006; Reitner 2007). New dating methods for moraines using surface exposure dating (SED) with stable isotopes from Beryllium (^{10}Be) suggested an age > 16 cal kyr BP for the Gschnitz stadial placing it into the pollen zone of the Oldest Dryas and, on a northern hemispheric scale, correlates this stadial with the cold ice-rafting event of Heinrich 1 of the North Atlantic (Ivy-Ochs et al. 2006). The Heinrich 1 cold event began at about 17.9 cal kyr BP (Sarnthein et al. 2007) and lasted until the beginning of LGI, which corresponds with the Greenland Interstadial 1 (GI-1) in the GRIP oxygen isotope event stratigraphy from Walker et al. (1999). Hence, Heinrich 1 mainly correlates with the sub-zone GS-2a of the Greenland Stadial 2 (GS-2). Gschnitz was the first marked glacier re-advance after large parts of the Central Alps had become ice-free (van Husen 2000, 2004). In contrast to Gschnitz, the preceding stadial of Steinach was in touch with glacio-morphological features of ice-decay in the large valleys (e.g. Mayr and Heuberger 1968; Reitner 2007) and radiocarbon dates from the former Traun (Draxler 1977; van Husen 1977) and Drau (Schultze 1984; Schmidt et a. 1998, 2002a,b; Huber et al. 2009) glacier retreat areas indicate that it occurred before 15,400 ± 470 ^{14}C kyr BP (= ~ 18,668 ± 503 cal yr BP). The recently described Clavadel/Senders glacier advance (type localities near Davos and Innsbruck) was placed between Gschnitz and LGI (Maisch in Ivy-Ochs et al. 2008, Studer 2005) and also the transfer of Daun (type locality Stubai valley SW of Innsbruck, Tyrol), which formerly together with Egesen was related to the Younger Dryas, into the Heinrich 1 complex is discussed in Ivy-Ochs et al. (2006).

Lake Längsee, which is located in the Carinthian lowland (Austria), has become a key study site for the stratigraphy and climate development after deglaciation south of the Alps for the following reasons: (1) Because of the location close to the LGM ice-margin (Lichtenberger 1959; van Husen 2004), fossil bearing sediments date back to early times of deglaciation. These have enabled the inference of a phase of climate warming older than Bølling, which formerly in the southern Alps was called Pre-Bølling (Schmidt 1975) and locally Längsee oscillation (Schmidt et al. 2001). Most recently, a diatom-based water temperature transfer function was created by Huber et al. (2009), and the inferred temperature curve was correlated with the Greenland oxygen isotope event stratigraphy of GRIP (Walker et al. 1999); (2) the presence of a tephra layer (Neapolitan Yellow Tuff = NYT) and varves enabled the dating of the mass expansion of birch to 14,270 cal. yr BP, which was defined as the lower boundary of LGI at Längsee (Schmidt et al. 2002a).

In the present study we focus on the early last glacial termination (for the term termination see Broecker 1984), which we define as the time window between LGM and LGI, characterised by the dominance of NAP. To evaluate the results from Längsee we have studied a sediment core section from Jeserzersee (also called Saissersee) on a time resolution of approximately 30 years applying a multi-proxy approach (diatoms, pollen, mineralogy and grain-size) and diatom-based water temperature inference. The reference lake was selected because of the observation of a *Juniperus*-rich pollen zone called Jeserzer-See-Schwankung by Schultze (1984) dated to 15,200 ± 400 ^{14}C yr BP (= 18220 ± 1027 cal yr BP) and the close distance (ca. 32 km) of Jeserzersee to Längsee and the LGM ice-margin of the Drau glacier.

2. Study site

Jeserzersee (64°37’35”N/14°02’00”E) is a small lake (13.3ha; maximum depth 6.6m; Jungwirth 1979), which is located at 593m a.s.l. north of the village Velden, near Wörthersee, in the Carinthian pre-alpine lowland (Austria) (Fig. 1). The geological basement is crystalline superimposed by Würmian morainic deposits that include also material from dolomitic and limestone areas. Lake-marl banks are present, which most likely were formed during warm periods rich in macrophytes. At present *Cladium mariscus*, which is characteristic for summer-warm lakes in Carinthia, dominates the littoral vegetation. Brossmann (1979) measured a mean lake pH of 7.6 in 1978.

3. Material and methods

3.1. Coring and dating

A 2-meter sediment core (JES) was taken from the deepest point of Jeserzersee in January 2006 with a modified Kullenberg piston sampler (Schultze and Niederreiter 1990). The plastic tubes (diameter 9 cm) were cut into halves (for details see Schmidt et al. 2002a) and sub-samples were taken at consecutive 0.5 cm intervals between 685 and 726 cm depth.

Within the 40 cm sediment sequence of interest, two bulk samples were dated using AMS radiocarbon (^{14}C) dating at the University of Kiel, Leibniz-Laboratory for Radiometric Dating and Stable Isotope Research. Bulk samples were used due to the absence of plant macrofossils suitable for dating, which could possibly have been caused by high decomposition. Additionally, we use two conventional ^{14}C dates from bulk samples given in Schultze (1984). For their stratigraphic position we used the pollen data. The four radiocarbon dates were calibrated into calendar years using the data set Intcal04 in the CALIB rev 5.01 program (Stuiver and Reimer 1993).

3.2. Diatoms

Sub-samples for diatom analysis were prepared by oxidation using H_2O_2 (Battarbee 1986). A few drops of the cleaned slurry were dried on cover slips and subsequently mounted on glass slides with Naphrax®. At least 300 diatom valves were counted using a light microscope (Leitz Diaplan) with 100x phase contrast oil immersion objectives (N.A. 1.32) and a magnification of 1250x. The main taxonomic source used for identification was Krammer and Lange-Bertalot (1986-1991). Wunsam et al. (1995) was additionally used for the identification of *Cyclotella* taxa and Schmidt et al. (2004b) for *Staurosira* taxa.

3.3. Pollen

To extract pollen from the sediment samples, 1 cm^2 of fresh material was treated with a bromide solution (saturated solution of $BrNa_3/HBr$ 9:1) prior to acetolysis. Carbonates were removed by 30 % HCl and silicates by 70 % HF treatment (Schmidt et al. 2004a). At least 300 pollen grains per sample were counted. *Pinus* taxa were differentiated according to Klaus (1972, 1977).

3.4. Mineralogy and grain-size analyses

Mineralogical analyses were conducted on air-dried and powdered bulk samples using X-ray diffraction (XRPD, AXS-Bruker D8) calibrated with the Rietveld-based quantitative XRD-software Siroquant®. The contents of quartz, mica, feldspar, gypsum, chlorite/amphibole, dolomite and calcite were calculated as percentages of total (100 %).

Three grain-size fractions (clay < 2 µm, silt 2-63 µm and, sand > 63 µm) were determined on untreated bulk sediments, which were suspended in Calgon® using a Laser-Particle-Analyser (Malvern Mastersizer2000®). Each result represents the mean of three single measurements. These were obtained after 3 min ultrasonic disintegration and simultaneous stirring and pumping through the measurement cell.

3.5. Data analysis

The diatom, pollen and mineralogical data were plotted using the computer program C2 1.5 (Juggins 2007). For the pollen data, we applied constrained optimal sum of squares partitioning using the program ZONE (Lotter and Juggins 1991), the resulting zones were used as a basis for the discussion of all stratigraphic proxy data.

For the diatom-based temperature reconstruction, Huber et al. (2009) amalgamated three diatom calibration data sets in order to include a wide variety of taxa and to obtain long gradients of key environmental variables: (1) The calibration data set of Wunsam and Schmidt (1995) consisting of alpine and pre-alpine lakes in Austria, Germany and northern Italy. Only lakes with a minimum of 4 measuring dates for mean summer epilimnetic water temperature (SEWT) were included from this data set. (2) The calibration data set from Schmidt et al. (2004b) consisting of 40 Austrian alpine lakes. (3) 10 lakes sampled in 2006/2007 following the procedures described in Schmidt et al. (2004b). The amalgamated calibration data set (ALPS06) totals 116 sites.

The significance of the environmental variables included in ALPS06 was tested in Huber et al. (2009) using canonical correspondence analysis (CCA) (ter Braak 1986) with forward selection and associated Monte Carlo permutation (999 unrestricted permutations, $P \leq 0.01$). The independent explanatory power of these variables was further tested by variance partitioning (Borcard et al. 1992). SEWT explained the largest proportion of variance in the diatom data and also had the most robust weighted averaging based inference model (LWWA – locally weighted weighted averaging) with an R^2_{jack} of 0.89 and a RSMEP of 1.82 °C. For a detailed account on model building see Huber et al. (2009).

4. Results

4.1 Pollen stratigraphy

The pollen stratigraphy of Jeserzersee was divided into the following six zones (Fig. 2). These zones were also used for the interpretation and discussion of the diatom and mineralogical data.

Zone 1 (726 – 724 cm):

This zone is characterised by high percentages of arboreal pollen, mainly *Pinus mugo* (up to ca. 40 %) and *P. cembra* (up to ca. 10 %). Poaceae (ca. 10-20 %) and *Artemisia* (ca. 15-30 %) show relatively high but fluctuating percentages.

Zone 2 (724 – 720 cm):

A marked decline in *P. mugo* pollen to ca. 10-15 % and a lesser decline in *P. cembra* to ca. 5-10 % can be observed. *P. sylvestris* (ca. 3 %) appears in the stratigraphy. Non-arboreal pollen (NAP) values increase to ca. 70 % due to a rise in Poaceae (to ca. 30 %) and *Artemisia* (to ca. 35 %). The abundance of *Juniperus* pollen begins to increase.

Zone 3 (720-711.5 cm):

Poaceae (ca. 14-24 %) and *Artemisia* (ca. 15-30 %) dominate the zone. *Juniperus* pollen increase further to ca 22 %, while NAP decrease in abundance from the previous zone. *Betula* pollen slowly increase during this zone.

Zone 4 (711.5 – 700 cm):

Poaceae and *Artemisia* still dominate the pollen assemblage at similar abundances than in zone 3. The abundances of *Juniperus* and *P. mugo* pollen decrease, and *P. cembra* (ca. 2-8 %) and *P. sylvestris* (ca. 0.5-6 %) occur at their lowest percent abundances. A further increase in *Betula* pollen can be observed reaching values of ca.14 %.

Zone 5 (700 – 692 cm):

A clear increase in *Juniperus* pollen (to ca. 35 %) and a decrease in *P. mugo* (to ca. 2-15 %) define this zone. Abundances of *P. cembra* and *P. sylvestris* are increasing to ca. 10 %. The percentage abundances of Poaceae (ca. 15-25 %) are still high and *Artemisia* (ca. 8-20 %) shows a minor decline.

Zone 6 (692 – 685 cm):

P. cembra (ca. 5-20 %) and *P. sylvestris* pollen (ca. 5-15 %) show fluctuating but high percentages, *P. mugo* is still frequent. The abundance of *Juniperus* pollen starts to decline (ca. 2-15 %). *Betula* pollen increase to 35 %, while NAP values decline (ca. 25-50 %) due to a major decrease in *Artemisia* (ca. 2-20 %).

4.2. Mineralogy and grain size (Fig.3)

Zone 1:

This zone is characterised by the increase of calcite. Quartz (ca. 20-30 %), mica (ca. 25-30 %) and feldspar (ca. 12-24 %) concentrations are high. The silt fraction (ca. 80%) is dominating.

Zone 2:

Calcite forms a marked peak to 20 % in this zone. The concentrations of sand start to increase at the expense of silt, while the concentrations of quartz, mica and feldspar decrease slightly from zone 1.

Zone 3:

Concentrations of sand level off at ca. 30 %. Calcite declines considerably (ca. 1-7 %) whereas dolomite remains at a similar level (ca. 10%) as before both resulting in a distinct peak of the dolomite/calcite ratio. Concentrations of quartz, mica and feldspar increase on average to 25, 32 and 20 %, respectively.

Zone 4:

Concentrations of sand decrease clearly throughout the zone to ca. 8 %, with a concomitant increase in silt. There is a marked peak in calcite concentrations to ca. 30 % in the middle of the zone. Concentrations of quartz, mica and feldspar decrease distinctly.

Zone 5:

Concentrations of sand increase markedly at the beginning of the zone to ca. 25% remaining at similar levels throughout the zone. A reciprocal decrease in silt can be observed. Calcite concentrations show another increase in this zone (to ca. 33%). There is a further slight decrease in the concentrations of quarz and feldspar, whereas mica increases slightly.

Zone 6:

Sand and silt concentrations are similar to the previous zone as are also those of quartz. Calcite concentrations drop clearly towards the top of the core; no calcite was found in the topmost sample. Concentrations of mica show a moderate increase during the upper half of the zone.

Concentrations of gypsum, chlorite/amphibole, dolomite and clay are low and show little change throughout the core; hence these are not further discussed.

4.3. Diatom stratigraphy and diatom-inferred SEWT (Fig. 4)

Zone 3:

No diatom valves were found in zones 1, 2 and the first half of zone 3. The latter half of zone 3 is characterised by the dominance of the benthic (bottom-dwelling) species *Amphora pediculus* (ca. 60-70 %). Other benthic species occurring at relatively high abundances include several *Staurosira* taxa, *Cocconeis neothumensis* and *Achnanthes conspicua*.

The diatom-inferred SEWT in zone 3 is ca. 15 °C.

Zone 4:

The dominance of benthic species continues in this zone. *Amphora pediculus* dominates the first half of the zone (ca. 60 %), but decreases markedly in abundance during the latter half to ca. 10 %. *Achanthes conspicua* and *Cocconeis neothumensis* show relatively high abundances in the middle of the zone (fluctuating around 15 and 7 %, respectively), whereas *Staurosira* taxa show highest abundances (30-60 %) in the upper part. *Diploneis parma* forms a well-defined peak (ca. 6 %) around the middle of the zone and *Amphora libyca* shows abundances around 20 % towards the top.

The diatom-inferred SEWT shows similar values to zone 3 at the beginning of this zone, decreases then clearly to 13.1 °C in the middle of the zone, increases again to 15.3 °C and shows another decrease towards the end of the zone to 13.8 °C.

Zone 5:

Amphora pediculus continues to dominate the diatom assemblages, however there is a marked increase during the first half of the zone in the abundance of planktonic (free-floating) taxa, especially *Cyclotella comensis* and *Cyclotella ocellata* (up to ca. 40 and 8 %, respectively), whereas *Staurosira* taxa decrease cleary. The benthic *Diploneis alpina* becomes abundant (ca. 6-33 %) during this zone.

Diatom-inferred SEWT is clearly highest during this zone reaching a value of 19.3 °C in the middle. Reconstructed values decrease towards the end of the zone to 16.2 °C.

Zone 6:

Amphora pediculus continues to dominate decreasing to < 20 % towards the top of the zone. *Staurosira* taxa are dominant during the first half of the zone (ca. 20 %), whereas the planktonic *Cyclotella comensis* increases markedly to ca. 60 % during the second half.

Diatom-inferred SEWT is relatively low at the beginning of this zone (lowest value 14.1 °C). SEWT increases clearly during the second half of the zone to a value of 19 °C in the topmost sample.

5. Discussion

For an easier comparison, we have transferred the pollen zones (PZ) to the different proxies and related them to the GRIP oxygen isotope event stratigraphy (Walker et al. 1999).

5.1. PZ1 – 3, related to the warmer sub-section of the Greenland Stadial 2 (GS-2b; 19,500 to 16,900 cal. yr BP)

Since the increased pine pollen (maximum 50 % of the total) at the bottom of the sediment core section (PZ1) is dominated by *Pinus mugo*, it indicates the successional development of an alpine dwarfed pine belt due to climate warming rather than originating only from enhanced long-distance pine pollen transport. The corresponding peak in calcite supports the suggestion of increased warming assuming that calcite originates from biogenic calcite precipitation. The calcite peak coincides also with the following increase of pollen of Poaceae (PZ2). They could originate from steppic habitats indicating a warmer, drier climate or from littoral areas of the lake rich in Poaceae (e.g. developing reed beds). The following pollen succession from increased *Juniperus*, which is more cold tolerant than pine, in PZ3 to a moderate increase in NAP in PZ4 indicates a step-wise climate deterioration. The assumption of this deterioration is supported by the mineralogy and grain size analysis. The increasing allochthonous elements during PZ3, which indicate running water impact (quartz, sand fraction) and/or physical weathering (feldspar, mica), suggest enhanced influence from the catchment (Schmidt et al. 2008). Also the marked peak in the dolomite/calcite ratio supports the suggestion of enhanced allochthonous influx. According to the ^{14}C age of 14,361 ± 65 yr BP the boundary between the decrease in *Juniperus* and increase in NAP lies around 17,222 ± 442 cal yr BP. Assuming our dating is reliable, the results from Jeserzersee fit well with the climate development at Längsee (LAE, Fig. 2). The pine pollen increase at the bottom of the core section of JES likely correlates with the warming during the so-called Längsee oscillation (Schmidt et al. 1998) followed by a step-like climate deterioration (*Juniperus* - NAP). Huber et al. (2009) related the diatom-inferred summer epilimnetic water temperatures (SEWT) in Längsee with the oxygen isotope event stratigraphy from the GRIP ice-core (Walker et al. 1999). It was assumed that the Längsee oscillation correlates with the warmer sub-section (GS-2b) of the Greenland Stadial 2 that lasted from 19,500 to 16,900 cal yr BP. Schultze (1984) dated the cross-over between the curves of slightly decreased *Pinus* and increased *Juniperus* in a pollen profile from Jeserzersee to 15,200 ± 400 ^{14}C yr BP (= ~ 18,220 ± 1027 cal yr BP). This date is in accordance with the Längsee oscillation. Schultze (1984) called the phase rich in *Juniperus* "Jeserzer-See-Schwankung" (Jeserzersee interstadial). However, the coarse sampling intervals (5 cm) in Schulze (1984) did not show the separation into two *Juniperus* phases, whereas the fine sampling interval in our study allowed for this differentiation (ca. PZ3 and PZ5). These two *Juniperus* phases indicate different climatic responses where the older phase suggests climate deterioration. Overall, the results from Jeserzersee are in agreement with indicators of early ice-decay in the Drau glacier area as shown by kame terraces overriden by local glacier advances similar to Steinach 150 km upstream from the moraines of LGM in the area of Lienz (e.g. Reitner 2003).

5.2. PZ4-6, related to the colder sub-section of the Greenland Stadial 2 (GS-2a; 16,900 to 14,700 cal yr BP)

The diatom record in JES started during the climate deterioration towards the end of GS-2b. The absence of diatom frustules during the warmer Längsee oscillation could be explained by diatom dissolution. For example, diatom dissolution occurred in the high alpine lake Schwarzsee ob Sölden (Tyrol) during warm periods of the Holocene. It correlated with the formation of siderite ($FeCO_3$) (Koinig, personal communication). In the JES core, the section corresponding to ca. PZ1- PZ3 had a distinctly reddish-brownish colour suggesting high concentrations of iron. Diatom dissolution has also been observed in anoxic Finnish lakes rich in iron (Meriläinen 1969, “iron-meromixis”).

Comparable to Längsee, the diatom-inferred SEWT curve of JES shows two colder phases (ca. PZ4 and PZ6) that are divided by a warmer phase (PZ5). The latter at Jeserzersee is rich in *Juniperus* (Fig. 2). The whole sequence, which at Längsee was called “Längsee cold period” was correlated by Huber et al. (2009) with the sub-section GS-2a of the Greenland Stadial 2 according to Walker et al. (1999). The Längsee cold period at both sites (JES and LAE) was correlated with the pollen zone of the Oldest Dryas (Schmidt et al. 1998, 2001). The diatom stratigraphy of the cold phases of JES is dominated by benthic taxa such as *Amphora pediculus* and several *Staurosira* taxa, the latter occurring frequently in arctic/high alpine lakes with prolonged ice cover. In contrast, the warm period in between (PZ5) is defined by a marked increase in planktonic taxa (expecially *Cyclotella comensis* and *C. ocellata*), which are associated with a longer growing season due to their open-water life form (Smol and Cumming 2000; Sorvari et al. 2002; Rühland et al. 2003).

The mineralogy indicates a subdivision of the older cold phase (PZ4), as it is divided by a calcite peak and shows a marked change in grain-size. As previously in PZ1, we assumed that increased calcite indicates calcite precipitation by warming. Although the diatom record does not indicate a pronounced temperature increase, one single sample corresponding with the calcite peak shows higher (> 10 %) abundance of planktonic diatoms (*C. comensis*) suggesting a slight increase in temperature (see discussion above). The lower part of the cold phase PZ4 was likely wetter than the upper part following the calcite peak. This is indicated by a significant increase of the small grain-size fraction in the upper part of the zone at the expense of sand due to less input from the catchment via erosion.

The younger cold phase indicated by diatoms (lower part of PZ6), which follows the period of warming (PZ5), is not clearly reflected in the pollen record, although a slight increase in NAP can be observed. The cold-resistant *Juniperus* could have masked the short-term climate fluctuation indicated by diatoms. However, diatoms, as many lower aquatic organisms, generally react more sensitively to minor changes in their environment (e.g. climate change) compared to terrestrial vegetation. Analogous to pollen also the mineralogy shows only a slight decline in calcite (693-689 cm).

At both sites Längsee and Jeserzersee, the younger cold phase after the period of warming (PZ5 in JES) is followed by a transitional phase ending with the mass expansion of *Betula* dated to 14,270 cal yr BP at Längsee (lower boundary of LGI at Längsee; Schmidt et al. 2002a). The transitional phase is characterised by the increase in *Pinus cembra* and *P. sylvestris* pollen at the expense of *P. mugo* indicating the beginning establishment of sub-alpine pine belts in the course of rising timberline. Single *P. sylvestris* probably were associated with *Betula*, which dominated the initial phase of reforestation. Planktonic diatoms increased clearly in abundance as did the diatom-inferred summer water temperatures. The onset of the transitional phase at Jeserzersee was dated by Schultze (1984) on a bulk sample with conventional ^{14}C to 13,850 ± 310 BP (= ~ 16,599 ± 967 cal yr BP). The uppermost pollen samples rich in birch (684 – 685 cm) from JES dated with AMS ^{14}C to 13,101 ± 55 yrs BP (= ~ 15,562 ± 328 cal yr BP) fit well with this dating. The increase in quartz, mica and feldspar at the top of the core section of JES (Fig. 3, PZ6), could indicate increased erosion and a change towards slightly wetter climate conditions.

Interpreting the results from Längsee and Jeserzersee during GS-2a, respectively Heinrich 1, in terms of glacier stratigraphy, we could suggest an older, possibly tri-partite, stadial phase and a younger, less pronounced one, which are separated by a distinct period of warming.

The ^{10}Be surface exposure dating of the moraine at the type locality of Trins (Gschnitz valley, Tyrol) suggested that the Gschnitz stadial began approximately 15,900 ± 1400 cal yr BP if not somewhat earlier (Ivy-Ochs et al. 2006). The cold phase of JES just below the warming period rich in *Juniperus* (PZ5) fits best with the model predictions of cold and dry (continental) climate conditions that were inferred for Gschnitz. Ivy-Ochs et al. (2006) suggested a precipitation for Gschnitz that must have been two-thirds less than today and summer temperatures lower by 8.5 to 10 °C. The minimum inferred SEWT of 13.2 °C in JES fits well with this temperature decline when we use the water temperature measurement of 21-23 °C during June 1978 measured by Kusel-Fetzmann and Nouak (1979). It is also in agreement with the SEWT inference at Längsee (Huber et al. 2009). However, in the case that the older cold phase of JES correlates with Gschnitz, our results suggest a slight tri-partition and a shift from wetter to dryer conditions. These patterns are similar to the Younger Dryas in the Austrian Alps (Schmidt 1981) even though the Gschnitz stadial was much colder and probably dryer (Ivy-Ochs et al. 2006). It is unclear whether the partially split structure of the lateral morains of Gschnitz (Mayr and Heuberger 1968; Ivy-Ochs et al. 2006) could be interpreted as a sign of two different advances during Gschnitz that are separated by a warmer period (e.g. a tri-partition).

If we assume that the younger cold phase following the period of warming in JES (PZ5) and LAE corresponds with the Clavadel/Senders stadial, there is no indication of an additional cooling period during the transitional phase before the Late Glacial Interstadial (Daun?, Ivy-Ochs et al. 2006). However an increase in precipitation at the transition to LGI is visible.

6. Conclusions

The multi-proxy stratigraphies and inferred climate development from Jeserzersee (JES) spanning the time interval from approximately 19,000 to 15,000 cal yr BP correlate well with the described climate development from Längsee and with the GRIP oxygen isotope event stratigraphy established by Walker et al. (1999) (Tab. 1). Lake Jeserzersee, which is about 30 km away from the LGM ice margin of the Drau glacier in Carinthia (Austria) and from the reference lake Längsee, must have become ice-free earlier than the Längsee oscillation. This oscillation was correlated with the warmer sub-section (GS-2b) of the Greenland Stadial 2 starting about 19,500 cal yr BP. Towards the top it shows a step-like climate deterioration, which could correlate with the onset of the cold ice rafting event of Heinrich 1 in the North Atlantic dated to

17,900 cal yr BP. Climate deterioration culminated during the following so-called "Längsee cold period", which was correlated with the sub-section GS-2a of the Greenland Stadial 2 lasting from approximately 16,900 to 14,700 cal yr BP, and with Heinrich 1. The Längsee cold period was, however, climatically heterogeneous. In accordance with the results from Längsee, and as the result of the high time resolution in JES it shows an older, possibly tri-partite, stadial phase and a younger, less pronounced cold event, both separated by climate warming. The older cold phase most probably correlates with the Gschnitz stadial and the younger one could correlate with the Clavadel/Senders glacier advance in the Alps. The more rapid response of aquatic organisms (diatoms) to short-term climate changes compared to the terrestrial vegetation rich in the cold-resistant *Juniperus,* could explain why the cold event during younger GS-2a is not reflected in the pollen record of Jeserzersee. The younger cold phase is followed by a transitional phase characterised by increased pollen of birch and pine and increased planktonic production of diatoms, indicating a successive increase in temperature. There is no indication of an additional cooling phase, but the mineralogical record suggests a slight increase in precipitation at the top of the core section dated to ca. 15 cal kyr BP.

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Tables

Table 1: Radiocarbon dates (^{14}C, * from Schultze 1984), pollen zones and climatic characterisation of the sediment core section from Jeserzersee (JES) in relation to the Längsee (LAE) stratigraphy, alpine stadials (Ivy-Ochs et al. 2006), Heinrich 1 cold event from the North Atlantic (Sarnthein et al. 2007) and the isotope event stratigraphy of the Greenland ice-core GRIP (Walker et al. 1999)

^{14}C years BP	JES PZ	Climatic characterisation	LAE06	Zones	Alpine Stadials	Ice-rafting event North Atlantic	GRIP
13,101 ± 55 13,850 ± 310*	6	increasing temperature and precipitation	Oldest Dryas	Längsee cold period	?	Heinrich 1	GS-2a
		cold			Clavadel/ Senders ?		
	5	warm			?		
	4	cold dry			Gschnitz		
		warmer					
14,361 ± 65		cold wet			?		
	3	temperature decrease wet		Längsee oscillation			GS-2b
15,200 ± 400*	2	warming					
	1						

Figures

Figure 1:

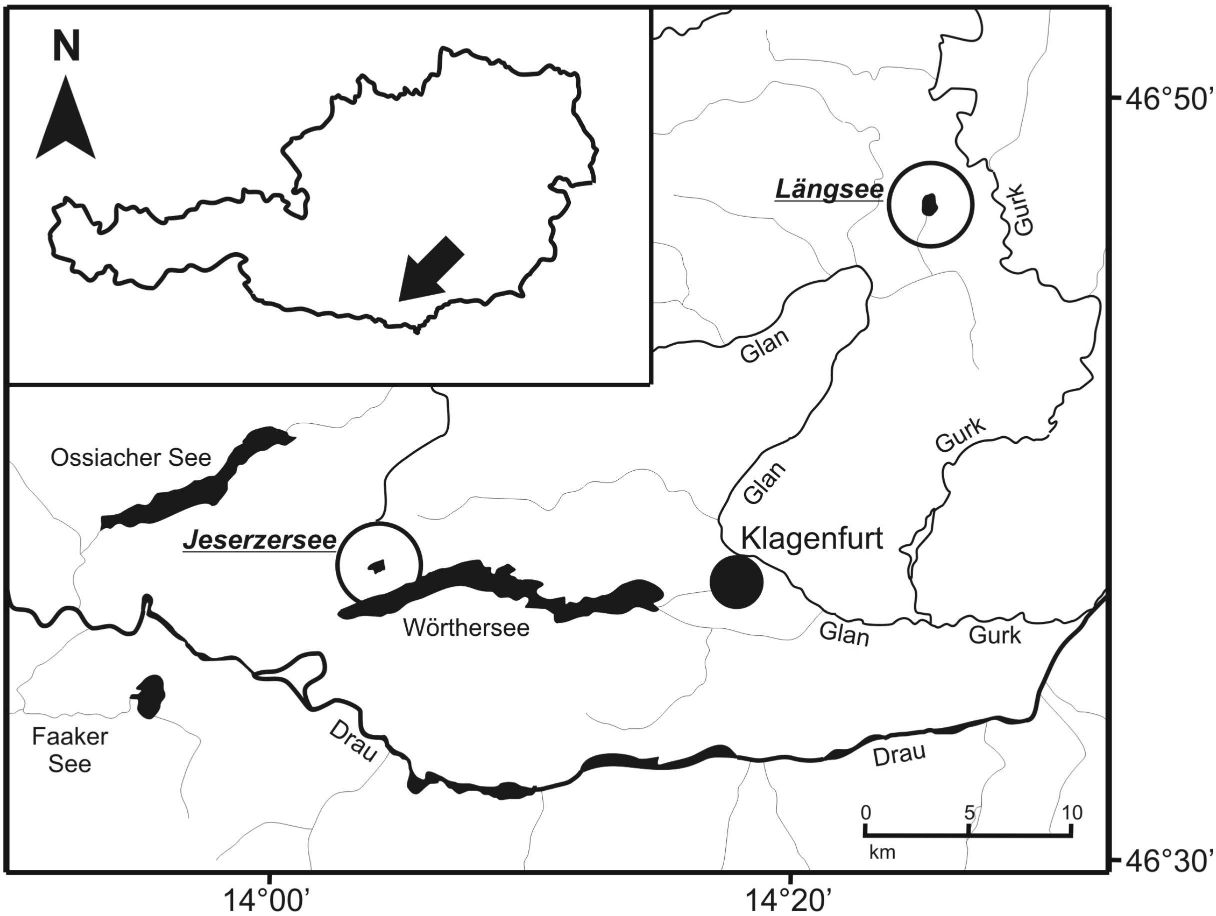
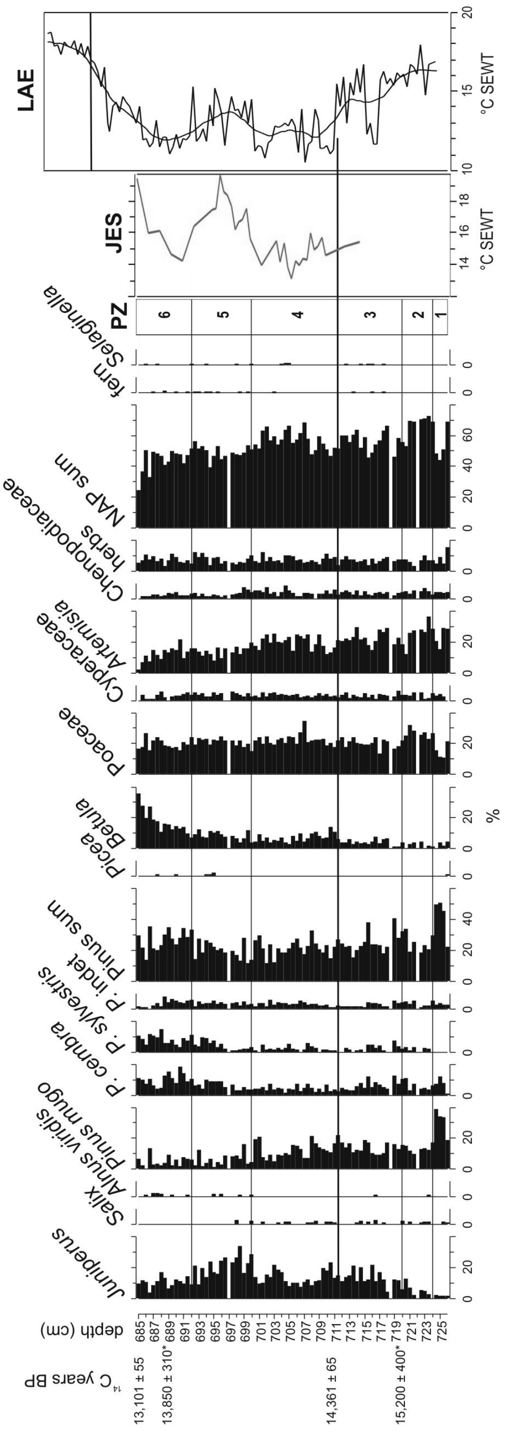
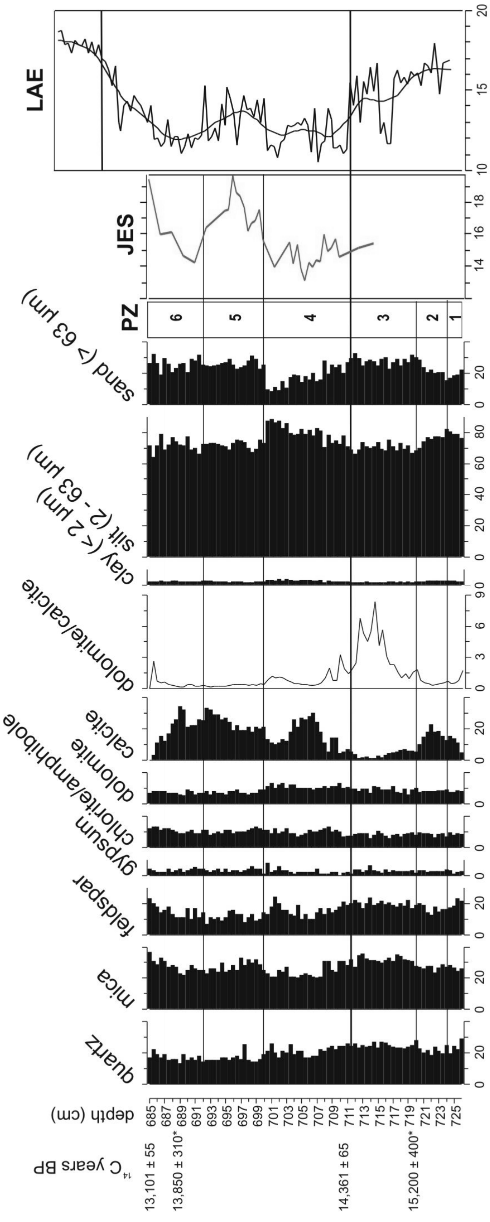


Figure 2:



¹⁴C years BP
13,101 ± 55
13,850 ± 310*
14,361 ± 65
15,200 ± 400*
depth (cm)
685
687
689
691
693
695
697
699
701
703
705
707
709
711
713
715
717
719
721
723
725
Juniperus
Salix
Alnus viridis
Pinus mugo
P. cembra
P. sylvestris
P. indet
Pinus sum
Picea
Betula
Poaceae
Cyperaceae
Artemisia
Chenopodiaceae
herbs
NAP sum
fern
Selaginella
PZ
1
2
3
4
5
6
JES
LAE
°C SEWT
%

Figure 3:



¹⁴C years BP
13,101 ± 55
13,850 ± 310*
14,361 ± 65
15,200 ± 400*
depth (cm)
685
687
689
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695
697
699
701
703
705
707
709
711
713
715
717
719
721
723
725
quartz
mica
feldspar
gypsum
chlorite/amphibole
dolomite
calcite
%
dolomite/calcite
ratio
clay (< 2 µm)
silt (2 - 63 µm)
sand (> 63 µm)
%
PZ
1
2
3
4
5
6
JES
°C SEWT
LAE
°C SEWT
10
15
20

Figure 4:

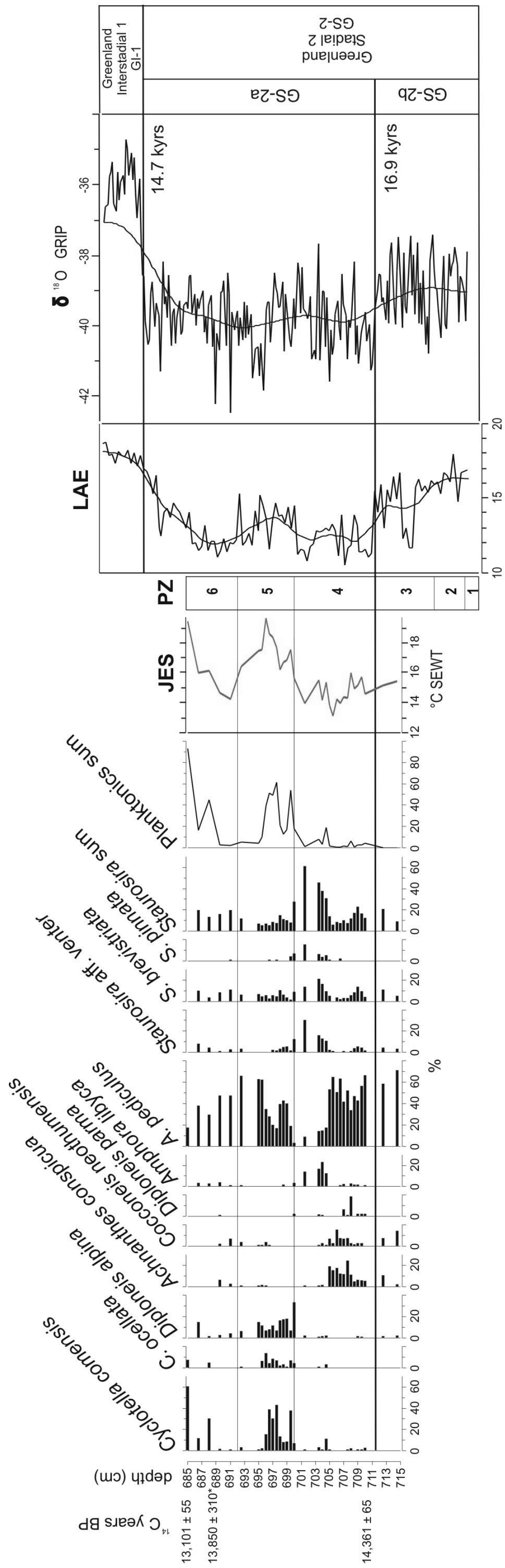
Greenland Interstadial 1 GI-1
Greenland Stadial 2 GS-2
GS-2a
GS-2b
14.7 kyrs
16.9 kyrs
δ ¹⁸O GRIP
-36
-38
-40
-42
LAE
10
15
20
°C SEWT
PZ
6
5
4
3
2
1
JES
12
14
16
18
°C SEWT
Planktonics sum
Staurosira sum
S. pinnata
S. brevistriata
Staurosira aff. venter
A. pediculus
Amphora libyca
Diploneis parma
Diploneis neothumensis
Cocconeis conspicua
Achnanthes alpina
Diploneis alpina
C. ocellata
Cyclotella comensis
%
depth (cm)
685
687
689
691
693
695
697
699
701
703
705
707
709
711
713
715
¹⁴C years BP
13,101 ± 55
13,850 ± 310*
14,361 ± 65

Figure captions:

Figure1: Geographic position of Jeserzersee and Längsee in Carinthia, Austria

Figure 2: Radiocarbon dates (^{14}C, * from Schultze 1984), percentage diagram of the major pollen of the sediment core section from Jeserzersee (JES), pollen zones, and the diatom-based SEWT reconstructions of Jeserzersee and Längsee (LAE) (Huber et al. 2009)

Figure 3: Radiocarbon dates (^{14}C, * from Schultze 1984), mineralogy and grain size distribution of the sediment core section from Jeserzersee (JES), pollen zones, and the diatom-based SEWT reconstructions of Jeserzersee and Längsee (LAE) (Huber et al. 2009)

Figure 4: Radiocarbon dates (^{14}C, * from Schultze 1984), percentage diagram of major diatoms of the sediment core section from Jeserzersee (JES), pollen zones, the diatom-based SEWT reconstructions of Jeserzersee and Längsee (LAE) (Huber et al. 2009), and the isotope event stratigraphy of the Greenland ice-core GRIP (Walker et al. 1999)

How fast do diatoms and chrysophyte cysts that are used as palaeolimnological indicators respond to present global warming in alpine lakes?

In prep.

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Hydrobiologia Special Issue –
'Global Change Impacts on Mountain Lakes'

Kerstin Huber: Field work, taxonomy and counting of cysts 2006/2008, data analyses (except species richness), figures, writing

Abstract

The study compared the diatom and chrysophyte cyst assemblage percentage composition in sediment surface and sediment trap samples from two sampling dates ten years apart in an Austrian alpine lake (Unterer Wirpitschsee, 1700 m a.s.l., Niedere Tauern). The compositional changes in these organisms were related to those in water temperature and chemistry in order to track the range and speed of changes related to global warming that happened during the decade 1998 - 2008. Fragilariaceae appeared to be particularly sensitive to climate change. In both diatoms and chrysophyte cysts slight compositional changes were observed. However, these were not statistically significant, and could not be related to the minor changes in the environment. Possible reasons for this are that (i) years within the decade differed extremely in temperatures, (ii) minor environmental changes did not exceed the reaction thresholds of the taxa, (iii) limitations in species differentiation could have caused loss in information, and (iv) the investigated lake is not located at a climatically sensitive ecotone.

Introduction

Global warming is occurring at a far greater amplitude in the Alps when compared to global data (Beniston et al., 1997). The mean annual air temperature rise in the Austrian Alps during the last 50 years related to global warming is approximately 0.9°C (Auer et al., 2007). Even small changes in the chemical and physical properties of alpine lakes are assumed to cause significant changes in the organisms inhabiting these lakes (Lotter et al., 1997, 1999; Schmidt et al., 2004b). Diatoms and resting stages of chrysophytes (cysts) are abundant and well preserved in alpine lake sediments and they are sensitive to climate change (Smol & Cumming, 2000). Hence, both fossils are used as palaeolimnological indicators to quantitatively track trends in climate-driven environmental variables using weighted averaging (WA) regression and calibration techniques (e.g. Birks, 1998). The rate and speed of change in alpine lakes that can be related to global warming, is, however, unknown. For this reason we have repeated the diatom and chrysophyte cyst assemblage, water temperature and chemical analyses in an Austrian alpine lake from ten years ago where we have applied the same methods.

Study site

Unterer Wirpitschsee (1700 m a.s.l.; 47°14’05’’N, 13°36’36’’E) is a small lake (2.72 ha; 8 m maximum depth) located in the Niedere Tauern, Eastern Central Alps (Austria). Alpine pastures surround the lake, which is placed on crystalline bedrock and close to metamorphic carbonates (Exner et al., 2005; Hejl, 2005). The lake is part of the Niedere Tauern (NT) lake training set, which was used for the calibration of diatoms and chrysophyte cysts against water temperatures and lake water chemistry (Schmidt et al., 2004a,b; Kamenik & Schmidt, 2005a).

Material and methods

Sampling, diatom and cyst analysis

A surface sediment sample (topmost 0.5 cm) was taken from the deepest point in Unterer Wirpitschsee using a gravity corer in summer 1999 and again in summer 2008. Additionally, sediment traps were exposed from summer 1998 to '99 and 2006 to '08 (for details see Schmidt et al., 2004a; Kamenik & Schmidt, 2005a).
Standard procedures were used to treat sediment surface and sediment trap samples (acid digestion with HCl and H_2O_2, Battarbee, 1986). Diatom slides of both sediment surface and trap samples were prepared with Naphrax mountant. At least 500 diatom valves were counted for each sample using a light microscope (Leitz Diaplan) with 100x phase contrast oil immersion objectives (N.A. 1.32) and a magnification of 1250x. Taxonomy of *Cyclotella* and *Staurosira* taxa followed Wunsam et al. (1995) and Schmidt et al. (2004b), for the identification of other taxa Krammer & Lange-Bertalot (1986-1991) was used.
Aliquot suspensions of the sediment trap samples were evaporated on glass cover slips, mounted on SEM stubs and sputtered with gold. At least 500 cysts were counted in each sample using a scanning electron microscope (Jeol JSM 35) equipped with an image analyzing system (QUANTEL Crystal) (Kamenik & Schmidt, 2005b) at a magnification of 3200x. Chrysophyte cysts were classified following the Atlas from Duff et al. (1995) and Wilkinson et al. (2001); similar cyst types were flagged by a PEARL prefix. Numbering of cysts not described in the Atlas or with doubtful assignment is in accordance with Kamenik (2001) and Kamenik & Schmidt (2005a). A collective category of unidentified cysts with oval or obovate shape is described as 'unidentified A'. Cysts lacking ornamentation or a collar, having regular or conical pores or a swollen pseudoanulus, were grouped according to size following the diameter ranges given by Kamenik (2001).

Environmental variables

Water chemistry was measured in autumn 1999 and 2008 (for details see Kamenik et al., 2001a and Schmidt et al., 2004a). Epilimnetic water temperature was measured in bi-hourly intervals using 8 bit MINILOG – TR thermistors (Schmidt et al., 2004b; Kamenik & Schmidt, 2005a) for one year ('98/'99) and two years ('06/'08). Measurements of the period '06/'08 were averaged to be comparable with the one-year period '98/'99. Dates of spring mixing (S_{mix}) and autumn mixing (A_{mix}) were defined as the first day after thawing or summer stratification when the mean daily water temperature was 4 °C (Schmidt et al., 2004b). Temperature readings under ice-cover were not used, because values varied considerably within the lake during that time, depending on whether the thermistor was frozen in the ice or not (Schmidt et al., 2004b). Temperature readings were averaged for the months May to October.

Numerical analyses

Species richness of all diatom and cyst samples was estimated using rarefaction analysis. This method gives realistic estimates of richness without any bias associated with the variability of count size between samples. The program RAREPOLL (Birks & Line, 1992) was used for the analysis.

Changes in species diversity of diatoms and cysts between ‘98/’99 and ‘06/’08 were assessed using the Shannon diversity index (Shannon & Weaver, 1949) and the Hill’s N_2 diversity index (Hill, 1973). The Shannon diversity index is a measure of the species number and the relative abundance of species in a sample. In contrast, the Hill’s N_2 diversity index is more sensitive to abundance variations of common species, because it comprises the effective occurrences of species in a sample.

Independent t-tests could not be applied to the diatom and cyst data to test the difference between samples from ‘98/’99 and ‘06/’08, as the data were not normally distributed even after square root or log+1 transformations. Nonparametric Mann-Whitney Rank Sum tests, which do not require assuming normality or equal variance, were applied instead.

Results

Water chemistry and epilimnetic water temperature

Water chemistry measurements showed a slight increase in pH from 7.7 to 7.9 and in alkalinity from 738 to 809 µeq l^{-1} from ‘98/’99 to ‘06/’08. The lake, which was highly oligotrophic already during the first measuring period, showed a minor decline in total inorganic nitrogen (TIN), dissolved nitrogen (DN) and total phosphorus (P_{tot}) (Table 1).

Average monthly temperatures were higher in the ‘06/’08 period compared to ‘98/’99 (see Fig. 1). Temperature increases ranged from 0.2 °C (August) to 2.7 °C (May). The date of autumn mixing occurred 2.5 days later and the date of spring mixing 21.5 days earlier in the ‘06/’08 period. Thus, the period between mixing dates was extended by 24 days (Table 2). The duration of ice-cover could not be clearly defined because of short melting-phases (increase in temperature up to 5°C, see Fig. 1a) alternating with frozen periods.

Chrysophyte cysts

In total, 72 cyst types were found in the sediment trap sample from 98/99 (Kamenik & Schmidt, 2005a). Of these, 28 occurred with a minimum of > 1 %. In ‘06/’08 73 cyst types were found, 18 with an abundance > 1 % (Fig. 2, Fig 3). The number of cysts with an abundance > 1 % had declined. No statistically significant difference was found between the two samples and species richness was consistent. However, both the Shannon and the Hill’s N_2 diversity indices showed a slight decline (Table 3).

Diatoms

In the sediment trap sample from ‘98/’99, 50 diatom taxa were differentiated, 17 of these occurred with a minimum of > 1 %. In the sample from ‘06/’08 again, 50 diatom taxa were identified, 16 with an abundance > 1 % (Fig. 4a, Fig. 5a). No statistically significant difference was found between both samples, but species richness was reduced from 50.0 in ‘98/’99 to 44.9 in ‘06/’08. Shannon and Hill’s N_2 diversity indices showed a slight decline (Table 3).

In the sediment surface sample of ‘98/’99, 55 diatom taxa were identified. Of these, 21 occurred with an abundance > 1 %. In ‘06/’08, 63 diatom taxa were found, 15 with an abundance > 1 % (Fig. 4b, Fig. 5b). As in the cyst data, the number of diatoms with an abundance > 1 % had declined. No statistically significant difference was found between both samples. However, species richness had declined between '98/'99 and '06/'08 from 53.5 to 51.8, and both the Shannon and the Hill's N_2 diversity index showed a decline (Table 3).

Discussion

Psenner & Schmidt (1992) and Koinig et al. (1998) suggested a rise in lake water pH for warmer years, which are usually characterised by drier conditions, increased evaporation, longer residence times, more stable stratification, higher biomass production and stronger reduction processes at the sediment-water interface. The weak trend of pH and water temperature increases at Unterer Wirpitschsee fits with this hypothesis. The slight increase in pH is not likely to be an analytical error, as it is supported by the concurrent increase in alkalinity.

Since nutrients remained nearly constant during both measuring periods (Table 1), they are not assumed to be responsible for the minor changes in species composition.

Smol et al. (2005) observed significant changes in species composition due to climate warming in lakes of the circumpolar Arctic over the past 150 years, mainly indicated by increases in planktonic diatoms (*Cyclotella*, *Tabellaria*, *Asterionella*) at the expense of small benthic taxa (*Fragilaria*/*Staurosira*, *Achnanthes*). The reduction of ice-cover and thus longer growing seasons as a result of temperature increase probably caused these shifts in species composition (Smol et al., 2005; Smol & Cumming, 2000; Sorvari et al., 2002; Rühland et al., 2003). At Unterer Wirpitschsee, the planktonic *Cyclotella* taxa showed no significant increase in abundance. Minor compositional changes are apparent mainly within the *Staurosira* taxa, with a rise in *S. pseudoconstruens*, *S. robusta* and *S.* Species 2 at the expense of *S.* aff. *venter*, *S. microstriata* and *S. pinnata*. Shifts in littoral benthic and tychoplanktonic Fragilariaceae (incl. *Staurosira*) assemblages could indicate changes in the formation of an ice-free moat (Smol, 1988, Smol & Cumming, 2000), which is the marginal open-water area during melting, due to warming. Schmidt et al. (2004b) estimated optima and tolerances for the length of ice-cover and pH of the *Staurosira* taxa in 45 lakes of the Niedere Tauern (Austria). When applying this dataset to our counts from Unterer Wirpitschsee, we obtained, however, no significant change in ice-cover and pH. The reasons could be (i) that ice-cover formation was interrupted by short-term melting phases as shown in the thermistor measurements (see Fig. 1a) and (ii) that the minor environmental changes between the two sampling dates did not exceed the reaction thresholds of the *Staurosira* taxa to ice-cover and pH as indicated by their range in tolerances (Schmidt et al., 2004b).

Similar to the diatoms, the cyst assemblages showed only a slight shift in species composition. High numbers of cyst types from collective categories (smooth types without ornamentation or collar and a regular or conical pore) were found, impeding ecological interpretations. For other cyst types (PEARL # 219), no autecological data is yet available (Duff et al., 1995). Cyst types PEARL # 113 and PEARL # 224, which both increased in abundance between the study periods in Unterer Wirpitschsee, are suggested to prefer cold oligotrophic lakes (Duff et al., 1995), but detailed preferences are not available. Cyst type 114c+d, which is known to bloom shortly after ice break (Kamenik et al., 2001b), decreased in abundance in '08, although the growing period was prolonged by an earlier date of spring mixing. When we apply the chrysophyte cyst calibration set from the Niedere Tauern (Kamenik & Schmidt, 2005a) to our counts from Unterer Wirpitschsee, we obtained no significant change in spring lake mixing and pH. The reasons for this are likely to be the same as for diatoms.

Conclusions

We found minor increases in seasonal water temperature and in pH and alkalinity between the sampling dates '98/'99 and '06/'08 in Unterer Wirpitschsee. Fragilariaceae appeared to be particularly sensitive to climate change. The minor changes in diatom and chrysophyte cyst assemblage composition showed, however, no significant relationship with the slight shifts in environmental conditions. This could have several reasons: During the decade, extreme temperature fluctuations occurred, such as the summer heat-wave 2003. Tolerances of most species showed a wide range, which exceeded the minor environmental changes. Collective categories in chrysophyte cysts and limited taxa differentiation in diatoms and chrysophyte cysts could have caused a loss in information. Additionally, the lake is not located at a climatically sensitive ecotone.

Acknowledgements

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Tables

Table 1: Water chemistry measurements in autumn ‘99 and ‘08

		98/99	06/08
Conductivity	$\mu S\ cm^{-1}$	86.0	83.7
pH		7.7	7.9
Alkalinity	$\mu eq\ l^{-1}$	738	809
TIN	$\mu eq\ l^{-1}$	10.5	8.9
SO_4^{2-}	$\mu eq\ l^{-1}$	101.7	113.9
Cl^-	$\mu eq\ l^{-1}$	3.7	5.4
Na^+	$\mu eq\ l^{-1}$	27.1	27.8
K^+	$\mu eq\ l^{-1}$	5.8	6.2
Mg^{2+}	$\mu eq\ l^{-1}$	111.3	152.1
Ca^{2+}	$\mu eq\ l^{-1}$	707.0	751.7
P_{tot}	$\mu g\ l^{-1}$	3.2	2.4
P_{dis}	$\mu g\ l^{-1}$	1.8	1.5
P_{part}	$\mu g\ l^{-1}$	1.4	0.9
DOC	$mg\ l^{-1}$	0.49	0.47
DN	$\mu g\ l^{-1}$	231	132
RDSi	$\mu g\ l^{-1}$	1072	1081

Table 2: Monthly average epilimnetic water temperature, dates of autumn and spring mixing

		98/99	06/08
T_{May}	°C	3.1	5.8
T_{June}	°C	7.4	8.8
T_{July}	°C	9.8	11.0
T_{August}	°C	10.4	10.6
$T_{September}$	°C	7.8	8.2
$T_{October}$	°C	5.4	6.2
A_{mix}	Julian days	298	300.5
S_{mix}	Julian days	508	486.5

Table 3: Species richness, Shannon and Hill's N_2 diversity indices of diatom and cyst sediment trap and sediment surface samples

		Species richness	Shannon index	Hill's N_2 index
Cysts	98/99	72.0	3.6	24.1
sediment trap	06/08	72.6	3.3	21.0
Diatoms	98/99	50.0	3.0	29.5
sediment trap	06/08	44.9	2.8	26.2
Diatoms	98/99	53.5	3.1	33.9
sediment surface	06/08	51.8	2.8	31.1

Figures:

Figure 1:

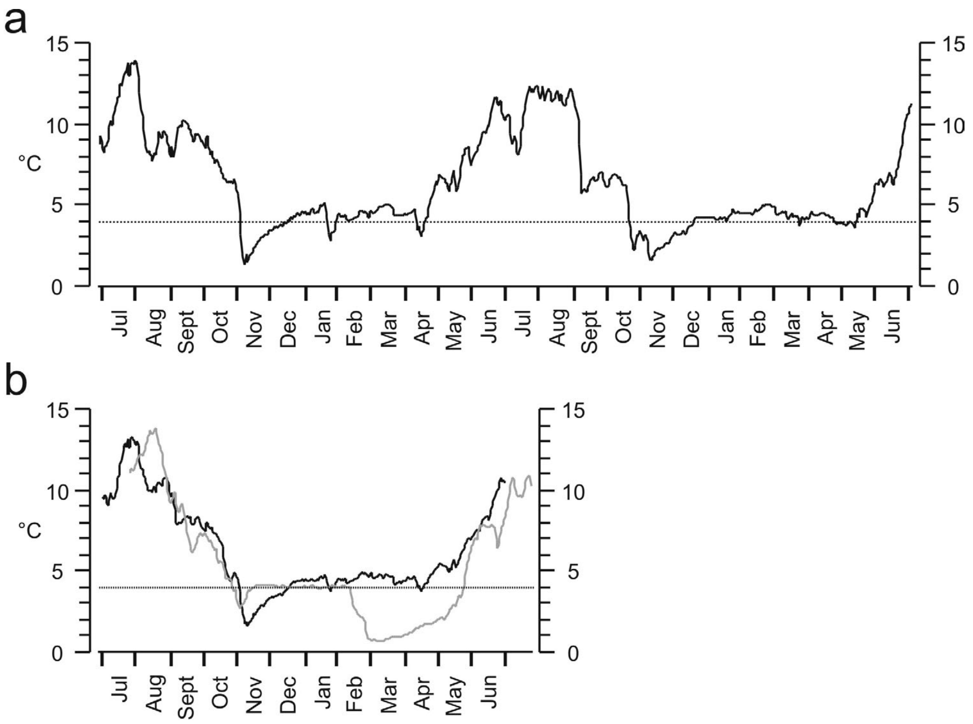

Figure 2:

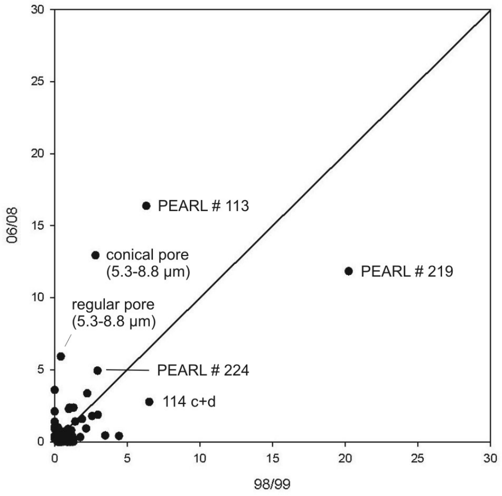

Figure 3:

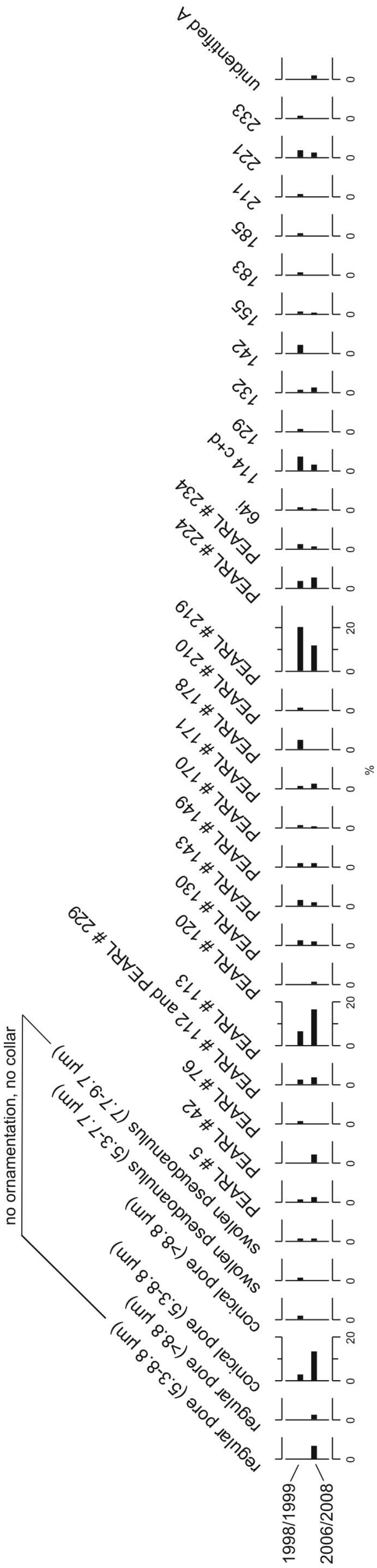
1998/1999
2006/2008
0
20
%
regular pore (5.3-8.8 µm)
regular pore (>8.8 µm)
conical pore (5.3-8.8 µm)
conical pore (>8.8 µm)
swollen pseudoannulus (5.3-7.7 µm)
swollen pseudoannulus (7.7-9.7 µm)
no ornamentation, no collar
PEARL # 5
PEARL # 42
PEARL # 76
PEARL # 112 and PEARL # 229
PEARL # 113
PEARL # 120
PEARL # 130
PEARL # 143
PEARL # 149
PEARL # 170
PEARL # 171
PEARL # 178
PEARL # 210
PEARL # 219
PEARL # 224
PEARL # 234
64i
114 c+d
129
132
142
155
183
185
211
221
233
unidentified A

Figure 4:

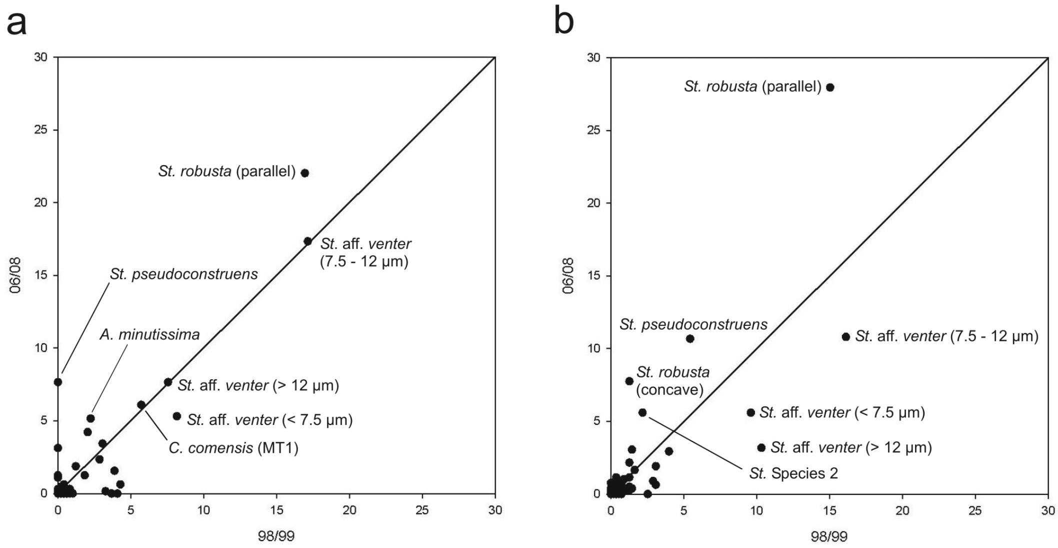
a
b
30
25
20
15
10
5
0
0
5
10
15
20
25
30
06/08
98/99
St. robusta (parallel)
St. aff. venter (7.5 - 12 µm)
St. pseudoconstruens
A. minutissima
St. aff. venter (> 12 µm)
St. aff. venter (< 7.5 µm)
C. comensis (MT1)
St. robusta (parallel)
St. pseudoconstruens
St. aff. venter (7.5 - 12 µm)
St. robusta (concave)
St. aff. venter (< 7.5 µm)
St. aff. venter (> 12 µm)
St. Species 2

Figure 5:

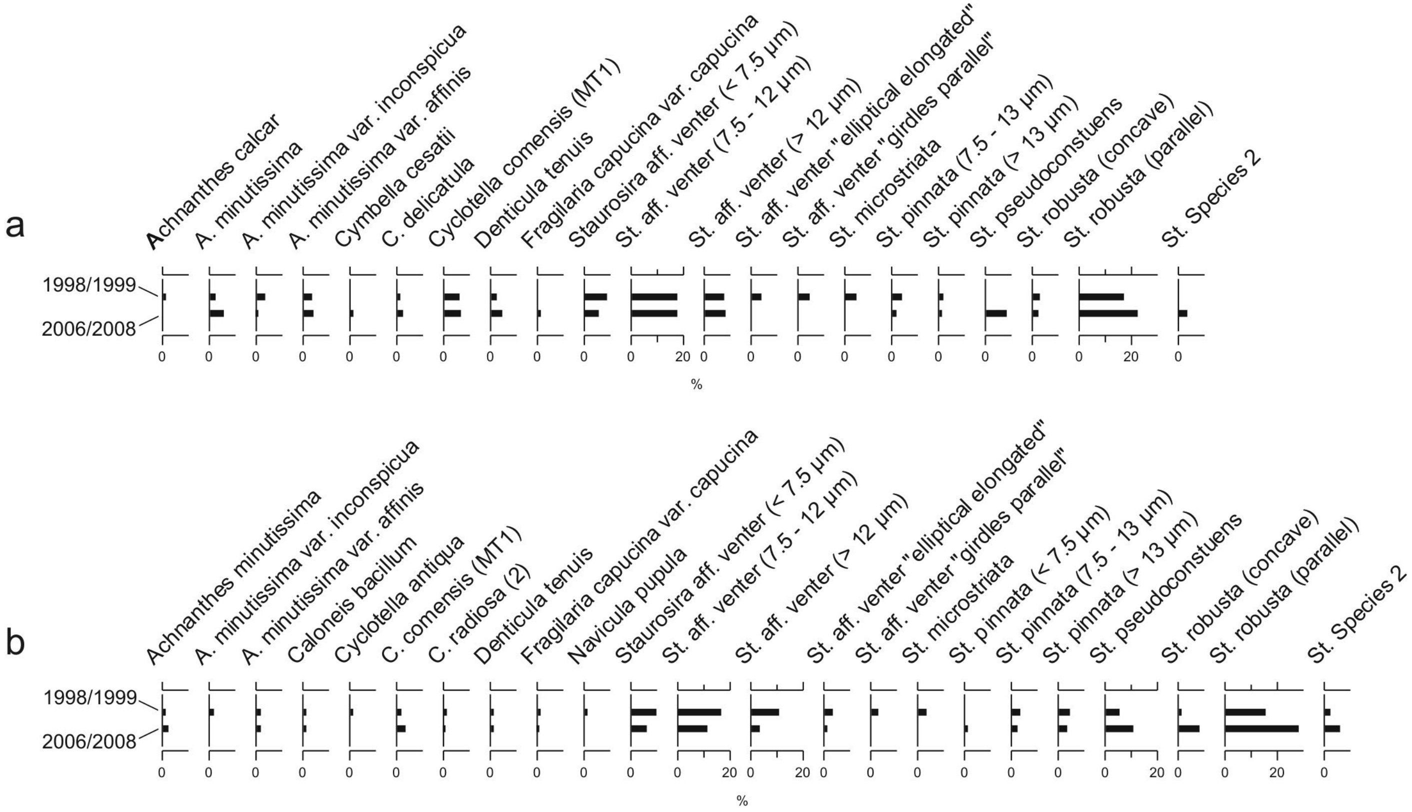
a
Achnanthes calcar
A. minutissima
A. minutissima var. inconspicua
A. minutissima var. affinis
Cymbella cesatii
C. delicatula
Cyclotella comensis (MT1)
Denticula tenuis
Fragilaria capucina var. capucina
Staurosira aff. venter (< 7.5 µm)
St. aff. venter (7.5 - 12 µm)
St. aff. venter (> 12 µm)
St. aff. venter "elliptical elongated"
St. aff. venter "girdles parallel"
St. microstriata
St. pinnata (7.5 - 13 µm)
St. pinnata (> 13 µm)
St. pseudoconstuens
St. robusta (concave)
St. robusta (parallel)
St. Species 2
1998/1999
2006/2008
0
20
%
b
Achnanthes minutissima
A. minutissima var. inconspicua
A. minutissima var. affinis
Caloneis bacillum
Cyclotella antiqua
C. comensis (MT1)
C. radiosa (2)
Denticula tenuis
Fragilaria capucina var. capucina
Navicula pupula
Staurosira aff. venter (< 7.5 µm)
St. aff. venter (7.5 - 12 µm)
St. aff. venter (> 12 µm)
St. aff. venter "elliptical elongated"
St. aff. venter "girdles parallel"
St. microstriata
St. pinnata (< 7.5 µm)
St. pinnata (7.5 - 13 µm)
St. pinnata (> 13 µm)
St. pseudoconstuens
St. robusta (concave)
St. robusta (parallel)
St. Species 2
1998/1999
2006/2008
0
20
%

Figure captions:

Figure 1: (a) Water temperature record from Unterer Wirpitschsee ‘06 to ‘08, dates of spring and autumn mixing are indicated (dotted line); (b) Water temperature record ‘98/’99 (grey) and averaged record ‘06/’08 (black)

Figure 2: Chrysophyte cyst distribution in sediment traps (‘98/’99 and ‘06/’08)

Figure 3: Cyst types (sediment trap), which occurred with a minimum of > 1 % in at least one sampling period

Figure 4: Diatom distribution in ‘98/’99 and ‘06/’08 in (a) sediment traps, and (b) sediment surface

Figure 5: Diatom species, which occurred with a minimum of > 1 % in at least one sampling period; (a) sediment trap; (b) sediment surface data

3. Published Abstracts

1st Central European Diatom Meeting 2007
Berlin, Germany, 23. – 25. March 2007
Abstract Book
Kusber, W.-H. & Jahn, R. (ed.)
Botanic Garden and Botanical Museum Berlin-Dahlem, Freie Universität Berlin
pp 28

Distribution and morphological variability of *Cyclotella*-taxa in the late glacial of Längsee (Austria) – Oral presentation

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Abstract:

A sediment core was taken from the profundal (21,5 m water depth) of Längsee, which is located in the Carinthian lowland (Austria), close to the end morains of the last Ice Age (Würm). Diatoms were sub-sampled in 0.5 cm intervals from the late glacial core section (ca. 13,000 – 15,000 cal. years before present). The diatom distribution is characterised by a change from *Staurosira*-rich assemblages during the Late-Pleniglacial cold period (> ca. 14,000 BP) to a *Cyclotella*-dominated section during interglacial climate warming. *Cyclotella*-taxa were identified using light and electron microscopy. We discuss the morphological variability of the *Cyclotella comensis, Cyclotella ocellata,* and *C. distinguenda* complexes in comparison with related taxa.

Kerstin Huber (presenter): Field work, taxonomy and stratigraphy of diatoms in Längsee, data analyses, writing

2^{nd} Central European Diatom Meeting (CEDIATOM2)

Trento, Italy, 12-15 June 2008
Abstract Book
M. Cantonati, A. Scalfi & E. Bertuzzi (eds.)
Trentino Nature & Science Museum
pp 85

The *Cyclotella comensis* complex in alpine and pre-alpine lakes

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Abstract:

Cyclotella comensis was described 1882 by Grunow from Lago di Como, Italy. The valves indicate major depressions associated with punctae in the central area, which are arranged in a more or less distinct radial pattern. Beside the type, Wunsam et al. (1995) distinguished four morphotypes in sediment surfaces of lakes from the Alps and pre-Alps, which they assigned to *C. comensis*. These types mainly differ in structure and ornamentation of the central area: (1) valves with a punctate radial ornamentation, (2) with a colliculate ornamentation, (3) with a tangentially undulated central area, (4) with an irregularly shaped ("frinsed") central area. These types are shown in light and electron microscopical (SEM) images. The morphotypes were related to chemical measurements in the lake data set; mean summer epilimnetic water temperature (T °C), pH, conductivity, ammonium and nitrate, and total phosphorus (TP). This lake data set was amalgamated with another one from mountain lakes in the Austrian Alps, where the same morphotypes were counted (Schmidt et al. 2004, and unpublished) resulting in a data set of, altogether 86 lakes. Ammonium and nitrate were summarized as total inorganic nitrogen (TIN). Statistical analyses were applied to determine if these morphotypes differ in their ecological preferences. We used "HOF", a gradient analysis using Huisman-Olff Fresco models with maximum likelihood (Oksanen & Minchin 2002). "HOF" species response curves indicated no significant difference in the ecological preferences between the *C. comensis* type and the morphotype (1), only a gradual one. The latter tends to prefer lower T °C, showing highest abundances in the colder, high-alpine lakes. Transitional morphological features are in agreement with the ecological gradient, and hence suggest conspecifity. The morphotypes (2), (3), and (4) showed higher temperature and conductivity optima and a tendency to higher nutrient concentrations (slightly mesotrophic).

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Wunsam S., Schmidt R. & R. Klee, 1995. *Cyclotella*-taxa (Bacillariophyceae) in lakes of the Alpine region and their relationship to environmental variables. *Aquat. Sci.* 57: 361-386.

Kerstin Huber (co-author): Data analyses/Huisman-Olff Fresco models, figures, LM images

APPENDIX B

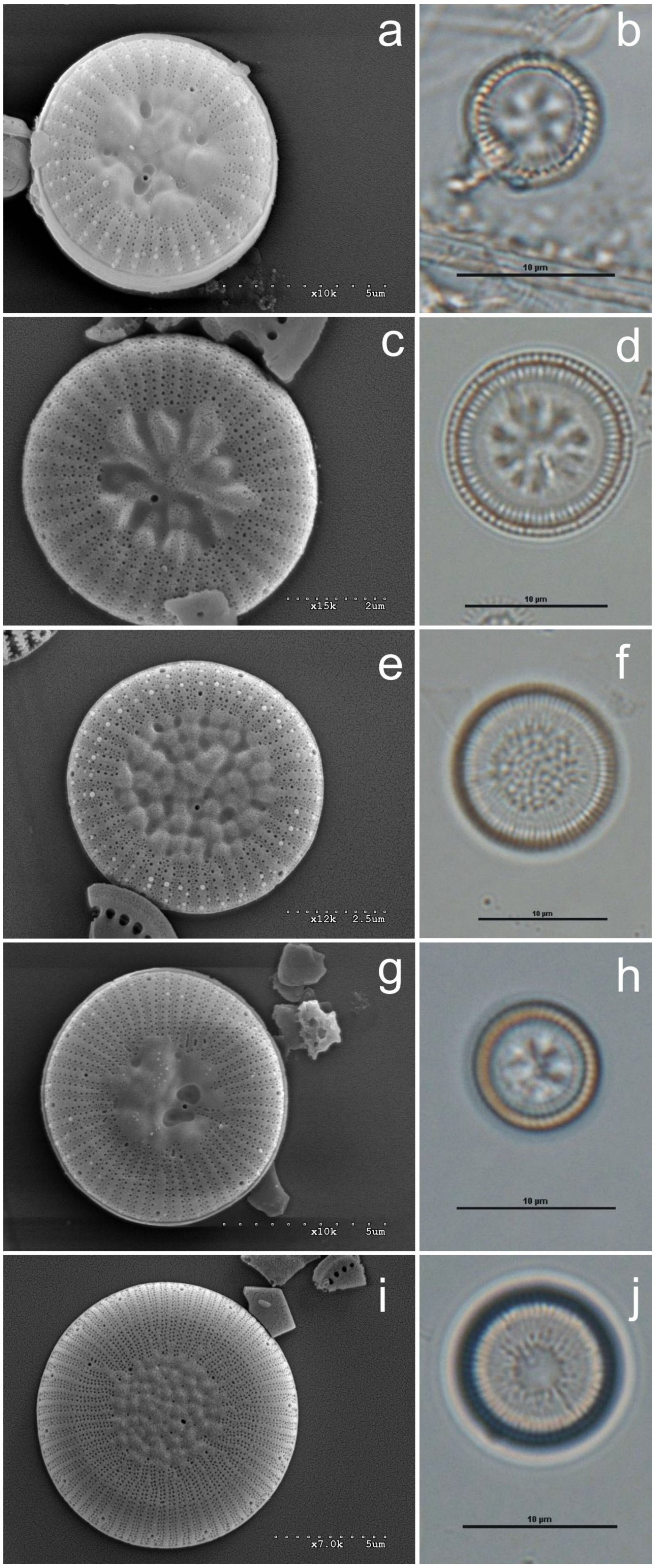

Fig. 1: SEM and LM images of *Cyclotella comensis* morphotypes; a, b *C. comensis* Grunow; c, d MT1; e, f MT2; g, h MT3; i, j MT4

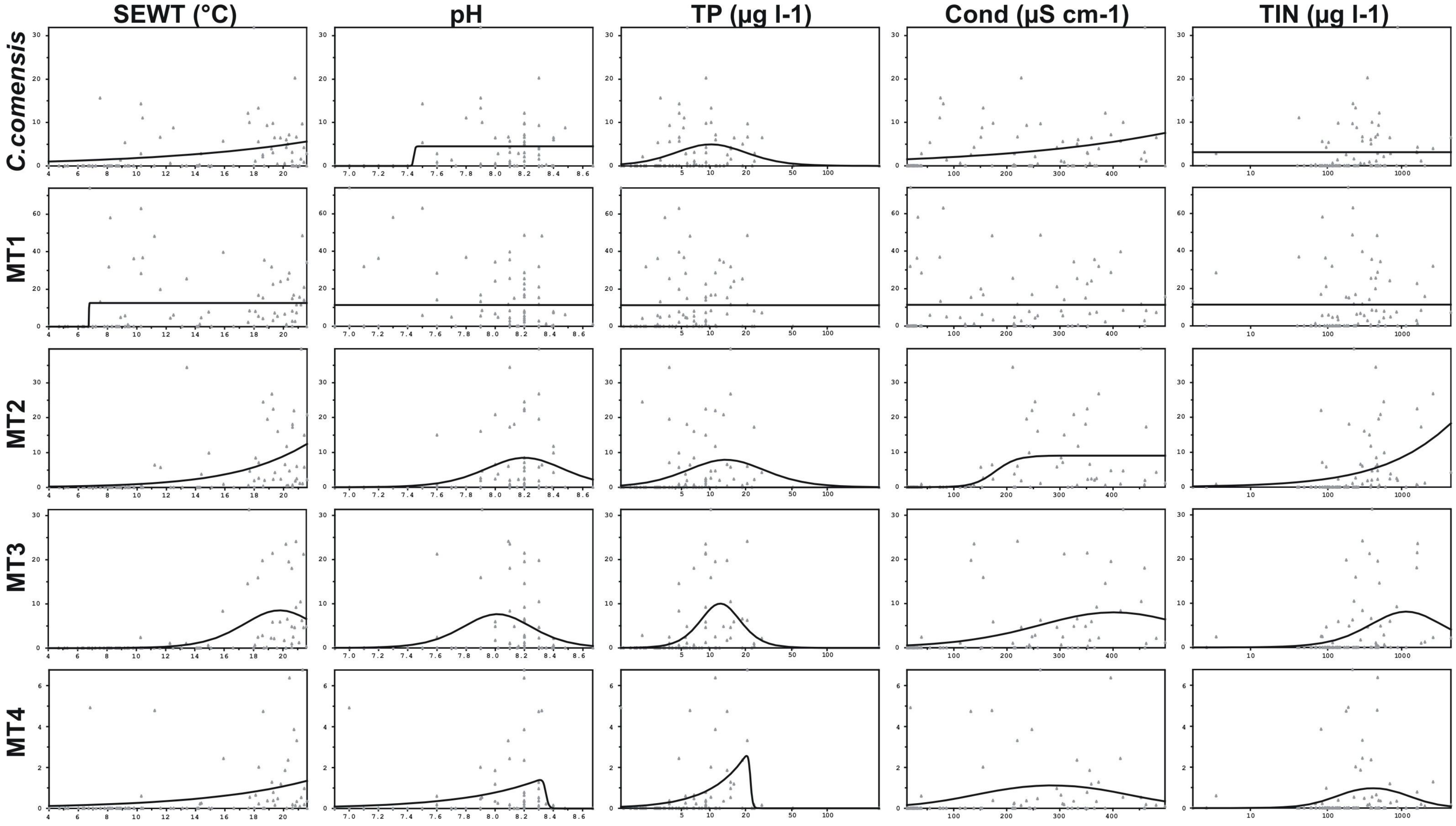

Fig. 2: Huisman-Olff-Fresco (HOF) species response curves of *C. comensis* morphotypes to environmental variables

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DIATOM-ENVIRONMENT RELATIONSHIPS IN ALPINE LAKES AND THEIR APPLICATION TO CLIMATE RECONSTRUCTION

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Abstract:

We have amalgamated diatom training sets from the Alps (Austria, Bavaria, Northern Italy), which have been published previously, in order to establish a transfer function for epilimnetic summer water temperature (SEWT). The 116 lakes investigated cover altitudes from 194 to 2309 m a.s.l. The SEWT-model (R^2_{jack} = 0,89, RMSEP = 1,82°C) was established with the use of weighted averaging techniques (LWWA) and applied to a lake sediment core from Längsee. The lake is located south of the Alps in the Carinthian lowland (Austria), close to the Würm-Pleniglacial ice margin. Since diatom-bearing sediments date back to the time of Termination, the time of interest spanned from the end of the Last Glacial Maximum (LGM) until early Late Glacial times (ca. 19 – 13 ky before present). Dating of this core section was performed using AMS radiocarbon (^{14}C) from terrestrial plant macrofossils, mainly seeds of birch. Warmer periods were dominated by planktonic *Cyclotella*-taxa, whereas during the colder periods *Staurosira* (mainly *S.* aff. *venter*) were most abundant. Valves similar to *Cyclotella plitvicensis*, which today is restricted to Lake Plitvice in Croatia, and which were called *C.* aff. *plitvicensis*, were found only in one highly oligotrophic hardwater- lake of the training set. Valves related to the *Cyclotella praetermissa*/*quadrijuncta* group, described from Late Glacial sediments in Austria and Bavaria, had, however, no recent analogues. Three major zones were distinguished in the Längsee core. The temperature inference was compared with the Greenland oxygen isotope ($\delta^{18}O$) curve (GISP2) and North Atlantic ice-rafting events: (1) a warm period, called Längsee oscillation, which probably corresponds to the younger part of climate warming following the LGM, (2) a subsequent marked cooling period, which fits with the GISP2 curve as well as with the Heinrich 1 cooling event between ca. 17,9 – 14,7 ky before present, and (3) warming of the Late Glacial Interstadial. The results of temperature inference obtained from Längsee were compared with those from another Carinthian lake core (Jeserzersee).

Kerstin Huber (presenter): Field work, taxonomy and stratigraphy of diatoms in Längsee, data analyses, writing

4. FWF Project Nr. 18595 – B17: "Klima- und Umweltentwicklung im späten Pleniglazial"

"Late-Pleniglacial climate and environmental evolution"

Kerstin Huber: Field work, taxonomy of chrysophyte cysts in newly sampled lakes, data analyses, figures, writing

4.1. Background information and project aims

Based on previous studies concerning the late glacial history of Längsee in Austria (Schmidt et al. 1998, 2002a, 2002b), the FWF Project “Klima und Umweltentwicklung im späten Pleniglazial” (Late-Pleniglacial climatic and environmental evolution; Project Nr. 18595 – B17) was launched in 2006. The overall goal of the project was to track changes in climate and environment during the late glacial in the southern Alps using information stored in a lake sediment core from Längsee. A multi-proxy palaeolimnological approach, using diatoms, chrysophyte cysts, ostracods, pollen, basic geochemistry and mineralogy was planned to provide a comprehensive picture of the lakes’ history with respect to climate and environmental changes in the south of Austria. Compared to previous studies, (a) a significantly higher time resolution, (b) improved dating, (c) quantitative inference, and (d) an extension of proxies were applied. For chrysophyte cysts and diatoms, on which this dissertation focuses, the existing calibration data sets (Schmidt et al. 2004a, 2004b; Kamenik and Schmidt 2005) were extended. The aim was to apply this extended calibration data set, with improved analogy, to the cyst and diatom assemblages of Längsee, to obtain a quantitative inference of seasonal climate (dates of spring mixing/S_{mix} and autumn mixing/A_{mix}, length of ice cover) and lake environment.

4.2. Calibration data sets for chrysophyte cysts and diatoms

Since not all diatom species and chrysophyte cyst types of the Längsee core occurred in the calibration data sets (Schmidt et al. 2004a, 2004b; Kamenik and Schmidt 2005) from the Niedere Tauern, 16 additional lakes were sampled in 2006/2007 (Tab.1), following the procedures described by Schmidt et al. (2004a, 2004b) and Kamenik and Schmidt (2005). Like Längsee, most of the 16 lakes are situated on carbonate bedrock, whereas the majority of lakes in the Niedere Tauern calibration data set are based on siliceous bedrock. Sediment traps with attached thermistors, measuring epilimnetic water temperature at 2-hour intervals, were exposed from summer 2006 to summer 2007 in all 16 lakes. Only 12 sediment traps with thermistors were found and recovered after one year of exposure, consequently no chrysophyte cyst data and thermistor readings were available for the other 4 lakes (Prebersee, Ödensee, Tristachersee, Weissensee). In 3 lakes (Kraigersee, Lustsee, Simssee) the water temperature during summer had partially exceeded the measuring range of the thermistors. In 2 lakes (Grundlsee, Lunzer See) A_{mix} and S_{mix} had occurred within one week. Thus, applicable thermistor readings were available for only 7 lakes (Ahornsee, Augstsee, Grafenbergersee, Laserzsee, Mönichsee, Steirersee, Vorderer Lahngangsee), which then could be amalgamated with the chrysophyte cyst and diatom calibration data sets of the Niedere Tauern (Schmidt et al. 2004b; Kamenik and Schmidt 2005). Diatom species data and environmental variables (with the exception of temperature) were available for 13 lakes (Tab 1). Due to these problems, the analogy between the calibration data sets and the Längsee core was unfortunately still dissatisfactory, despite the attempt to improve it.

Lake	Position
Ahornsee	47°28’00’’N – 13°46’56’’E
Augstsee	47°39’49’’N – 13°47’10’’E
Grafenbergersee	47°28’01’’N – 13°46’04’’E
Grundlsee	47°38’02’’N – 13°51’53’’E
Kraigersee	46°48’08’’N – 14°22’01’’E
Laserzsee	46°46’44’’N – 12°48’10’’E
Lunzer See	47°51’13’’N – 15°03’11’’E
Lustsee	47°48’37’’N – 11°17’45’’E
Mönichsee	47°46’06’’N – 13°27’12’’E
Ödensee	47°33’40’’N – 13°49’15’’E
Prebersee	47°11’05’’N – 13°51’26’’E
Simssee	47°52’22’’N – 12°14’22’’E
Steirersee	47°35’56’’N – 14°01’54’’E
Tristachersee	46°48’25’’N – 12°47’46’’E
Vorderer Lahngangsee	47°40’15’’N – 13°55’50’’E
Weissensee	46°42’24’’N – 13°20’28’’E

Table 1 Lakes sampled in 2006/2007

4.3. Multivariate statistics

All environmental variables in the cyst set and the diatom set were tested for skewness and, if necessary, $\log_{10}$ (x+1) transformed. Chrysophyte cyst and diatom abundances were square root transformed to stabilize their variances. The main environmental gradients in the chrysophyte cyst data set as well as in the diatom data set were represented by a number of highly inter-correlated variables. These variables were divided into three groups representing gradients of conductivity, temperature and productivity. A detrended correspondence analysis (DCA) (Hill and Gauch 1980) with detrending-by-segments and downweighting of rare species of the assemblages resulted in a gradient length of 4.7 (cysts) and 3.4 (diatoms) standard deviation (SD) units of species turnover, suggesting unimodality in the species data of both sets (ter Braak 1987; Birks 1995). Therefore we used canonical correspondence analysis (CCA) (ter Braak 1986), an ordination technique that assumes a unimodal species response with forward selection and associated Monte Carlo permutation (999 unrestricted permutations, $P \leq 0.01$) to test the significance of the explanatory variables. The independent explanatory power of each environmental variable was tested by variance partitioning (Borcard et al. 1992).

4.4. Results and discussion

4.4.1. Chrysophyte cysts

The results of the CCA (Fig. 1) with forward selection indicated that each of the three groups corresponding to the main environmental gradients in the data set could be represented by just one variable, namely pH, S_{mix} and DOC. The three variables explained altogether 18.1 % of the total variation in the cyst assemblages. Variance partitioning and associated permutation tests, however, show statistical significance of only one explanatory variable, namely pH. It explained 7.6 % of the variation in the chrysophyte cyst data. S_{mix} and DOC did not account for significant and independent fractions of variation.

The DCA graph (Fig. 2) of lakes in the Niedere Tauern and 7 newly sampled lakes with supplementary environmental variables showed that the Niedere Tauern calibration data set of chrysophyte cysts and the seven new lakes represent two separated subsets, which are not connected by intermediary lakes. The two subsets are separated mainly by pH, since the lakes in the Niedere Tauern are situated on siliceous bedrock, whereas the seven new lakes are situated on carbonaceous bedrock. The sampling period of the new lakes from summer 2006 to summer 2007 was exceptionally warm. Therefore the seven new lakes showed higher epilimnetic water temperature than lakes in the Niedere Tauern calibration data set at corresponding altitudes. Hence, the ice-cover period was much shorter (if existent at all) and the date of S_{mix} was earlier in spring. Due to these circumstances, higher pH and S_{mix} showed a spurious correlation in the calibration data set.

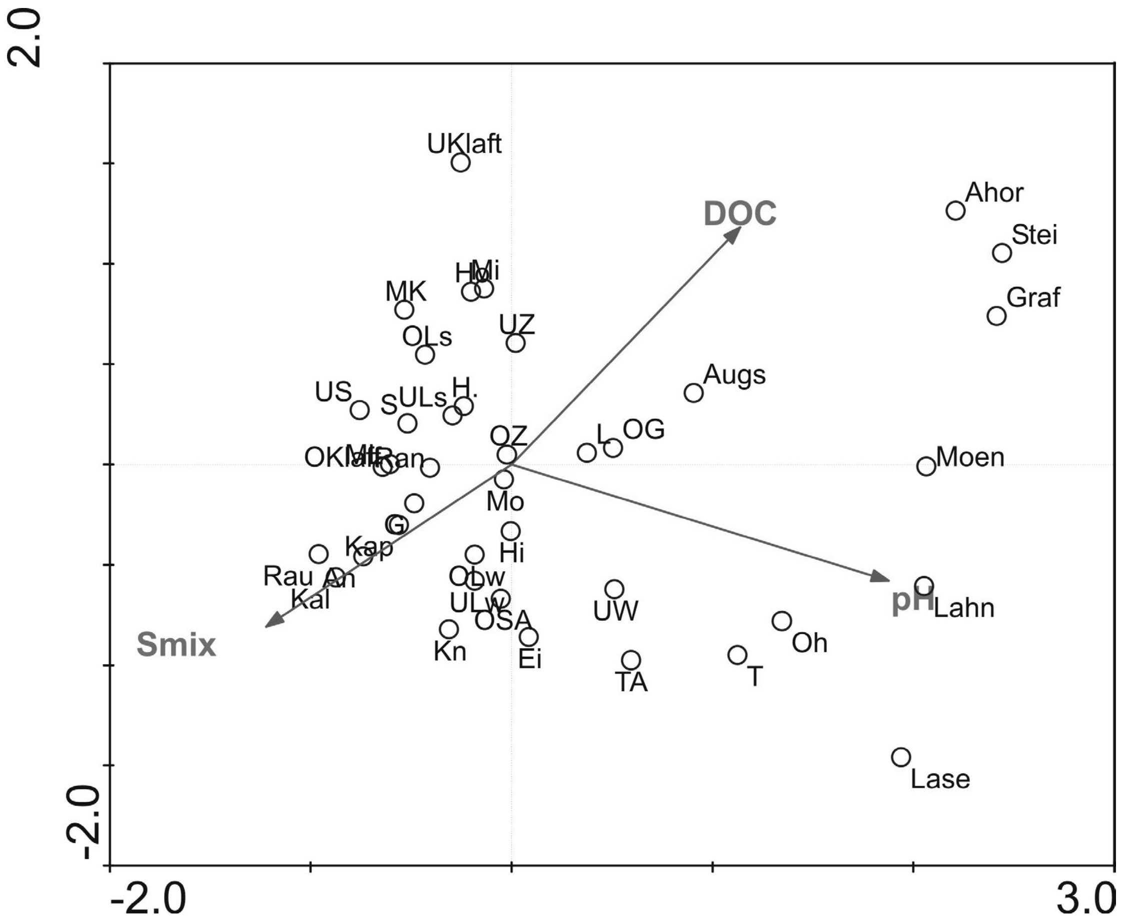

Fig 1 CCA with 29 lakes of the Niedere Tauern calibration data set and 7 lakes sampled in 2006/2007

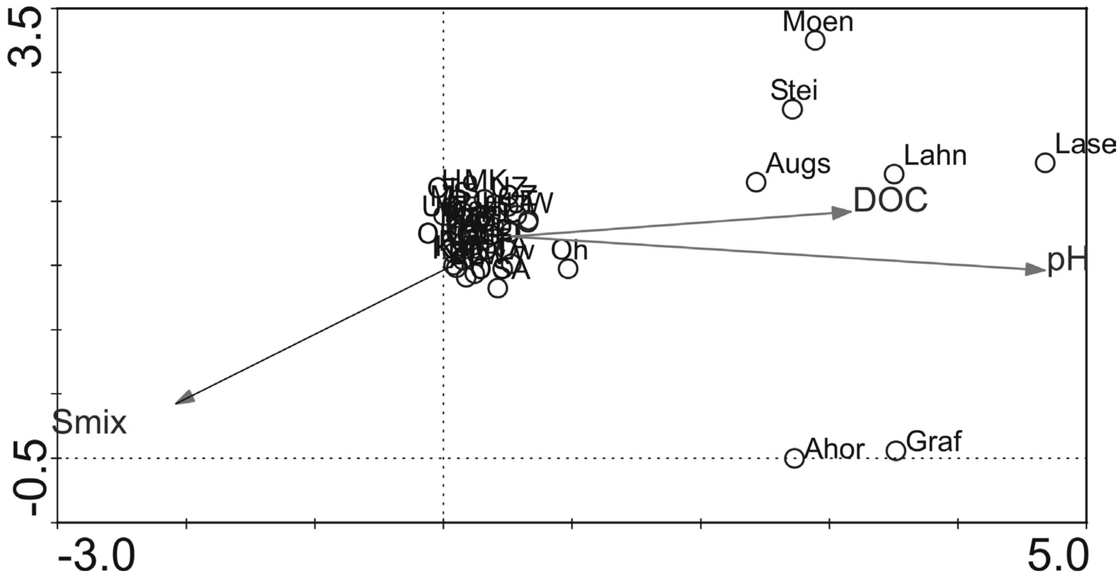

Fig. 2 DCA with 29 lakes of the Nieder Tauern calibration data set and 7 lakes sampled in 2006/2007. Environmental variables were added as supplementary variables to the analysis and hence have no effect on the position of sites and species in the ordination plot.

4.4.2. Diatoms

As in the chrysophyte cyst data, the results of the CCA (Fig. 3) with forward selection indicated that each of the three groups corresponding to the main environmental gradients in the diatom data set could be represented by just one variable, in this case pH, A_{mix} and DOC. According to variance partitioning and associated permutation tests, pH and DOC were highly significant, whereas A_{mix} was slightly less significant with a p-value of 0.008. The three variables explained altogether 16.3 % of the total variation in the cyst assemblages. pH explained most of the variance (7.4%), followed by DOC (3.7%) and A_{mix} (3.1%).

The DCA graph (Fig. 4) of lakes in the Niedere Tauern and 7 newly sampled lakes with supplementary environmental variables showed a separation of the two subsets, which was, however, not as strong as the separation observed in the chrysophyte cyst data.

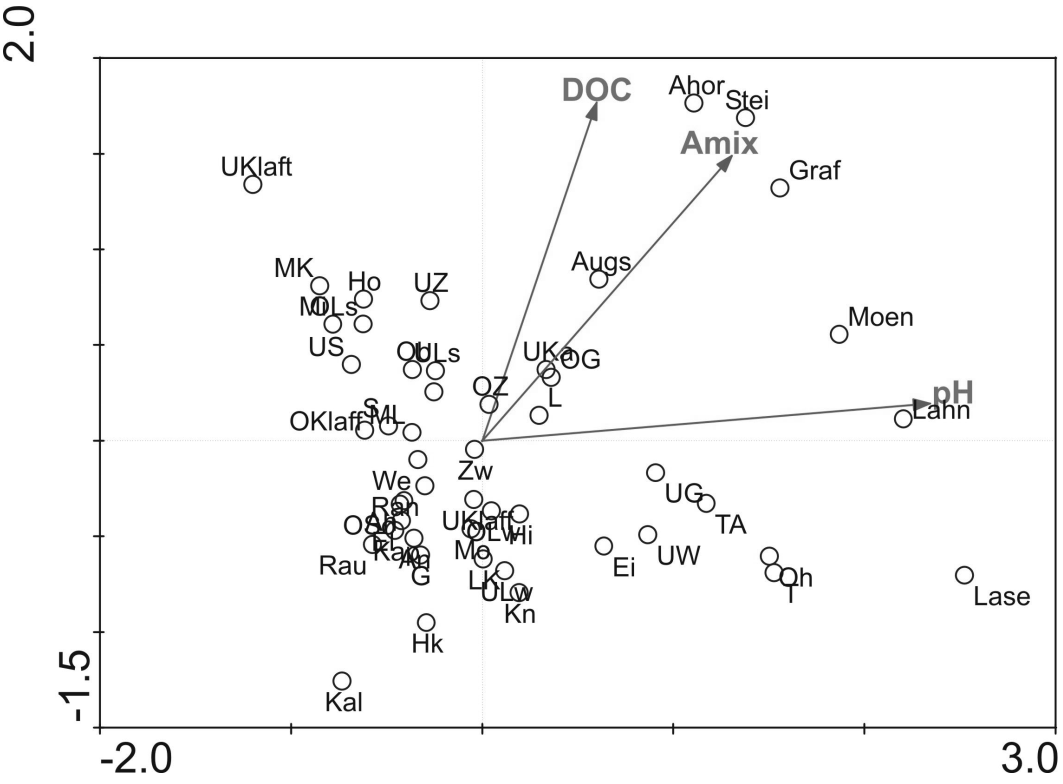

Fig. 3 CCA of 40 lakes of the Nieder Tauern calibration data set and 7 lakes sampled in 2006/2007 with supplementary environmental variables

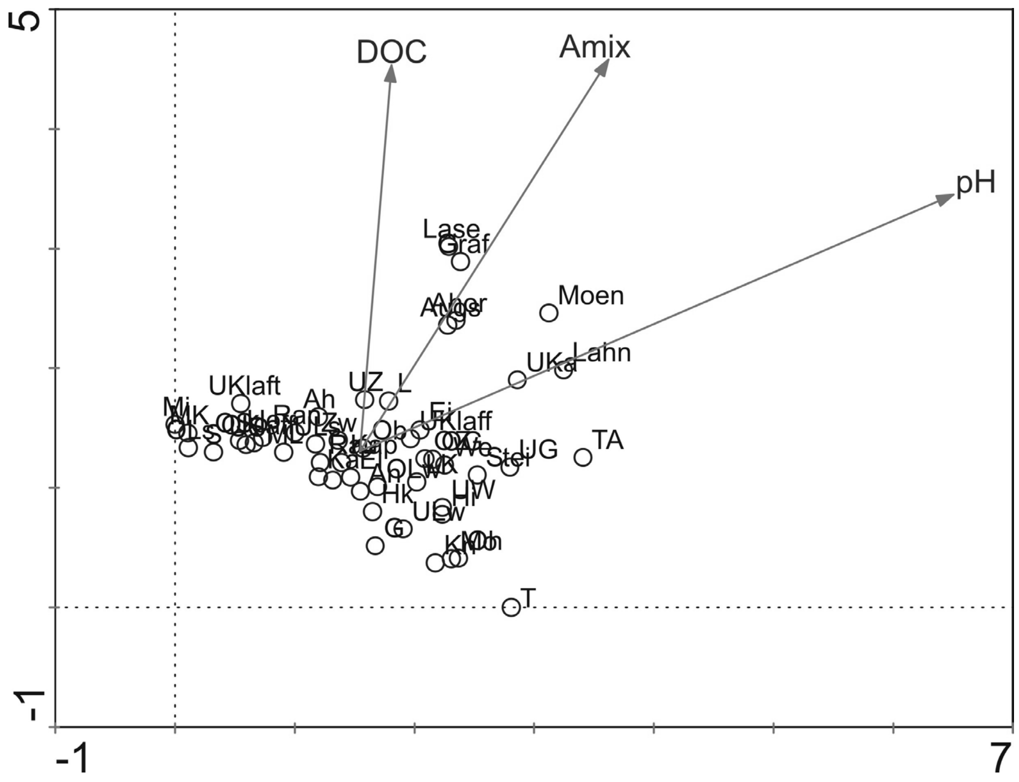

Fig. 4 DCA with 40 lakes of the Niedere Tauern calibration data set and 7 lakes sampled in 2006/2007 with supplementary environmental variables

4.5. Conclusions

Since S_{mix} did not account for a significant and independent fraction of variation in the chrysophyte cyst data, a reconstruction of this environmental variable for the Längsee core was not meaningful. According to variance partitioning, A_{mix} was significant in the diatom data, but explained much less of the variance than pH and DOC. Due to these problems with the calibration data sets of chrysophyte cysts and diatoms, it was not advisable to reconstruct S_{mix} and A_{mix}, or the length of ice cover for the Längsee core as was originally planned.

Instead we extended the calibration data set of diatoms by the diatom calibration data set of Wunsam and Schmidt (1995).

The diatom calibration set ALPS06 was amalgamated from the following:

- The Niedere Tauern calibration set of 40 alpine lakes (Schmidt et al. 2004b)
- The calibration data set from Wunsam and Schmidt (1995) of alpine and pre-alpine lakes in Austria, Germany and northern Italy. Only 66 lakes with a minimum of 4 measuring dates for mean summer epilimnetic water temperature (SEWT) were included. Grundlsee, Kraigersee and Weissensee, which had also been sampled in 2006/2007 were already part of this set.
- 10 new lakes sampled in 2006/2007. Thermistor readings for SEWT were available for 9 lakes (Ahornsee, Augstsee, Grafenbergersee, Grundlsee, Laserzsee, Lunzer See, Mönichsee, Steirersee, Vorderer Lahngangsee). Grundlsee was excluded, because it was part of the calibration data set from Wunsam and Schmidt (1995) as well. Lustsee and Simssee could be used, because SEWT measurements were available from local institutes (Bavarian Environmental Agency, Wielenbach).

This resulted in a calibration data set of 116 alpine and pre-alpine lakes (ALPS06). The analogy with the Längsee core was considerably improved. The calibration data set from Wunsam and Schmidt (1995) included less environmental variables than the Niedere Tauern calibration data set (Schmidt et al. 2004b). In addition to SEWT, the following variables exist for all lakes: pH, conductivity (COND), total inorganic nitrogen (TIN), total phosphorus (TP) and maximum depth (MD). This enlarged calibration data set covered a long gradient of temperature, conductivity and productivity. The five forward selected variables mean SEWT, pH, COND, TP and MD, accounted for significant and independent fractions of variation and explained altogether 21.6 percent of the observed variation in the diatom data (Fig. 5). (For more details see Huber et al. 2009).

In the DCA (Fig. 6) the separation of the subsets was still visible, but less pronounced with the lakes sampled in 2006/2007 located in between the two calibration data sets from Wunsam and Schmidt (1995) and Schmidt et al. (2004b).

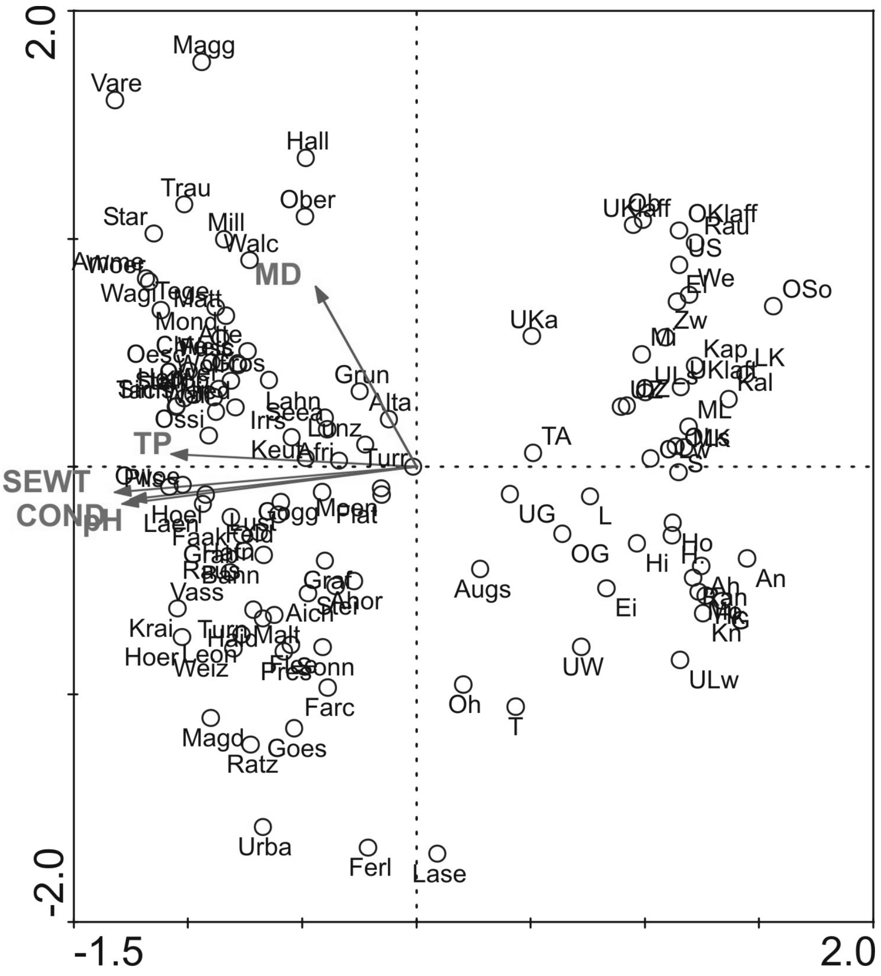

Fig. 5 CCA with 40 lakes of the Niedere Tauern calibration data set, 66 lakes of the Wunsam and Schmidt (1995) calibration data set and 10 lakes sampled in 2006/2007

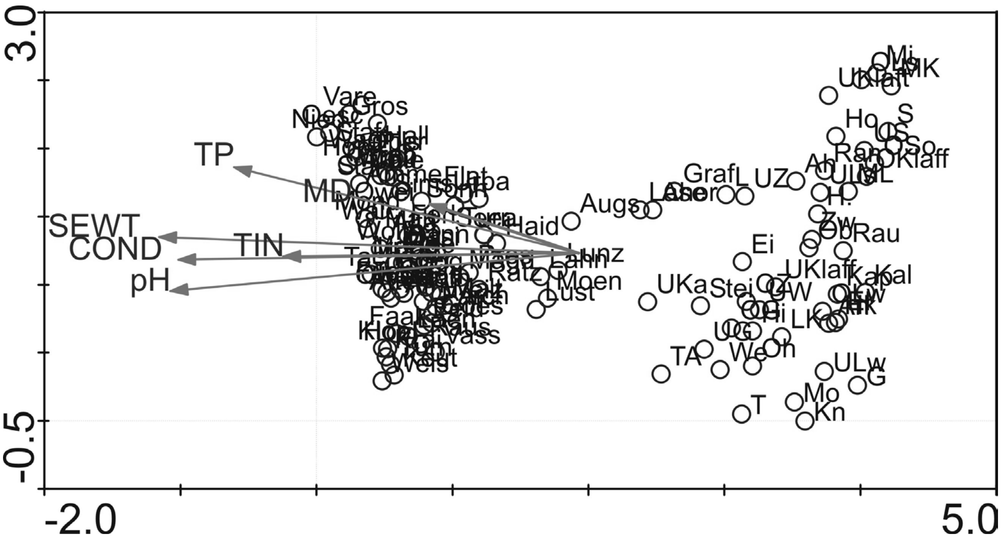

Fig. 6 DCA with 40 lakes of the Niedere Tauern calibration data set, 66 lakes of the Wunsam and Schmidt (1995) calibration data set and 10 lakes sampled in 2006/2007 with environmental variables plotted as passive variables

4.6. References

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5. Summary

In this study, calibrated indicator organisms (diatoms) were used to infer summer epilimnetic water temperatures (SEWT) from a sediment core of Längsee (Carinthia) for the early part of the last glacial termination (approximately 19 to 13 cal kyrs BP). Three data sets were amalgamated to create a super-set of 116 alpine and pre-alpine lakes for the reconstruction of SEWT. The results from Längsee were put into a larger northern hemispheric scale by comparison with the oxygen isotope record from the Greenland ice core GRIP showing a good correlation. Three major climatic sections were found in Längsee: A warming period (Längsee oscillation, approximately 19 to 17 cal kyrs BP), which probably correlates with the warmer sub-zone GS-2b of the Greenland Stadial 2 (GS-2). A subsequent climate cooling (Längsee cold period) corresponding to the colder sub-zone GS-2a of GS-2, the cold event Heinrich 1 from the North Atlantic, and partially with the Gschnitz Stadial in the Alps. The following warming period (Längsee late glacial interstadial) between approximately 14.5 and 13 cal kyrs BP is consistent with the Greenland Interstadial 1 (GI-1). Three minor climate fluctuations were found during the Längsee late glacial interstadial. Only the one related to the Gerzensee fluctuation from Switzerland showed a decline in SEWT. Discrepancies between aquatic organisms and pollen in respect to climate are probably caused by different response times, sensitiveness and tolerance against temperature.

Chrysophyte cysts related to meso-eutrophic conditions, cysts related to oligotrophic conditions and/or cold water, and cysts showing no preferences were differentiated in the Längsee core by comparison of the cyst stratigraphy with diatom-inferred SEWT and total phosphorus. Intra-specific differentiation was exemplarily studied in cysts and diatoms to show its value for future fine adjustment of calibration.

A sediment core from Jeserzersee was used as a reference and validated the results from Längsee.

To address the temporal inhomogeneity of the amalgamated diatom super-set, the rate and dimension of climate driven shifts were exemplarily studied in one lake. Minor changes in water temperature, -chemistry and species composition were found.

6. Zusammenfassung

In der vorliegenden Arbeit wurden mit Hilfe geeichter Kieselalgen (Diatomeen) in einem Sedimentkern des Längsees (Kärnten) Sommerwassertemperaturen (SEWT) für das Ende der letzten Eiszeit von ca. 19000 bis 13000 Jahren vor heute rekonstruiert. Für SEWT wurde durch Zusammenlegen dreier Kalibriersets (116 alpine und voralpine Seen) ein Super-Set generiert. Für die Einordnung der Klimadaten in einen nordhemisphärischen Rahmen wurde die abgeleitete Temperatur mit der Sauerstoff-Isotopenkurve aus dem grönländischen Eis (GRIP) korreliert und zeigte eine gute Übereinstimmung. Im Längsee wurden drei Klimaabschnitte unterschieden: Eine Warmphase (Längsee Oszillation, ca. 19000 bis 17000 Jahre vor heute), die wahrscheinlich der wärmeren Subzone GS-2b des Grönlandstadials 2 (GS-2) entspricht. Eine folgende Klimaverschlechterung (Längsee Kaltperiode) korreliert mit der kälteren Subzone GS-2a des GS-2, mit dem Kälteereignis Heinrich 1 im Nordatlantik, sowie teilweise mit dem Gschnitz Stadial der Alpen. Die folgende Erwärmung zwischen ca. 14500 bis 13000 Jahren vor heute ist mit dem spätglazialen Interstadial (SI) bzw. dem Grönland Interstadial 1 (GI-1) gleichzusetzen.

Von den kleineren Kälteschwankungen während des SI konnte nur die sogenannte Gerzenseeschwankung der Schweiz in der Temperaturrekonstruktion erfasst werden. Diskrepanzen in der Klimaresonanz zwischen aquatischen Organismen und Pollen sind vermutlich primär auf unterschiedliche Reaktionszeiten, Sensibilität und Toleranzverhalten gegenüber Temperatur zurückzuführen.

Im Vergleich zu den Diatomeen und den daraus abgeleiteten Variablen SEWT und Gesamt-Phosphor wurden im Längsee Dauerstadien von Goldalgen (Chrysophyceen-Zysten) mit Präferenz für oligotrophe Verhältnisse und/oder kühle Temperaturen, meso- bis eutrophe Verhältnisse, sowie Zysten ohne klare Präferenz unterschieden. Der Frage intra-spezifischer Differenzierung wurde sowohl bei den Chrysophyceen-Zysten als auch Diatomeen exemplarisch nachgegangen und Bedeutung für die zukünftige Verfeinerung in der Kalibrierung beigemessen.

Für die Validierung der Ergebnisse aus dem Längsee wurde ein Referenz-Kern aus dem nahen Jeserzersee herangezogen, der die Klimarekonstruktion des Längsees bestätigte.

Zur Frage der zeitlichen Inhomogenität des Diatomeen Super-Sets wurden Geschwindigkeit und Ausmaß klimatisch gesteuerter Veränderungen exemplarisch an einem See untersucht. Für die Untersuchungsdekade konnten geringe Veränderungen in der Artenzusammensetzung, dem Temperaturverlauf und dem Chemismus festgestellt werden.

7. Acknowledgements

Viele Menschen haben mich in den letzten Jahren auf beruflicher genauso wie auf privater Ebene unterstützt und so das Gelingen dieser Doktorarbeit erst möglich gemacht. Bei ihnen allen möchte ich mich herzlichst bedanken, insbesondere aber bei den Folgenden:

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8. Curriculum Vitae

Name:	Kerstin Huber
Current address:	Linzer Gasse 21/6, 5020 Salzburg
Place and date of birth:	Rotthalmünster, 27. Oktober 1979

Education:

2008	Upper Austrian Academy of Journalism
since 2006	Ph.D. study of Biology/Ecology, University of Vienna Ph.D. Thesis: "Late glacial climatic and palaeoecological investigations of Längsee (Austria) using diatoms and chrysophyte cysts"
2006	M.Sc. in Biology/Ecology M.Sc. Thesis: „Physical, chemical und biological investigations of soil crusts in the high-alpine Großglockner region"
2004	B.Sc. in Biology/Ecology.
2000 – 2006	Study of Biology/Ecology, University of Salzburg
1990 – 1999	High school, Pocking
1986 – 1990	Elementary school, Hartkirchen

Professional Experience:

since 2008	Writer for the magazine life+science
since 2006	Staff member and Ph.D. candidate, FWF project, working group Palaeolimnology (Head Prof. Roland Schmidt); assistant in public relations, Institute for Limnology, ÖAW, Mondsee, Austria
2005 – 2006	Technician, University of Salzburg, Austria
2001	Practical training at National Park Bayrischer Wald, Germany
1999	Practical training at Innes and Mt. Gambier National Parks, Australia

Awards:

2008	Writing contest award, magazine sciencegarden
2006	Austrian National Park Research Award; Federal Ministry of Agriculture, Forestry, Environment and Water Management and the Austrian National Parks
2006	Achievement grant, University of Salzburg

Publications:

Huber K., C. Kamenik, K. Weckström & R. Schmidt (accepted): Taxonomy, stratigraphy, and palaeoecology of chrysophyte cysts from a Late Glacial sediment core section of Längsee, Austria. Nova Hedwigia

Huber K., K. Weckström, R. Drescher-Schneider, J. Knoll, J. Schmidt & R. Schmidt (2009): Climate changes during the last glacial termination inferred from diatom-based temperatures and pollen in a sediment core from Längsee (Austria). Journal of Paleolimnology (DOI 10.1007/s10933-009-9322-y)

Schmidt R., Drescher-Schneider R., Huber K., Weckström K. (2009): Die Bedeutung des Längsees in Kärnten für die Rekonstruktion der Klima- und Seenentwicklung am Ende der letzten Eiszeit. In: Schmidt R., Matulla C., Psenner R. (Hg): Klima im Wandel – 20.000 Jahre Klimaentwicklung in Österreich (Proxis, Daten, Szenarien) - Vernetzung von Klimasignalen unterschiedlicher Indikatoren und Zeitskalen sowie instrumenteller Daten (PALDAT). Alpine Space – Man & Environment, Vol. 6, Innsbruck University Press, Innsbruck, pp 27-40

Huber K., R. Klee & R. Schmidt (2007): Distribution and morphological variability of *Cyclotella*-taxa in the late glacial of Längsee (Austria). Proceedings of the 1st Central European Diatom Meeting, Berlin 2007: 59-62.

Huber K., T. Peer, A. Tschaikner, R. Türk & J.P. Gruber (2007): Characteristics and function of soil crusts in different successional stages in alpine environments, outlined on an alpine lime scree in the Großglockner region (Austria). Mitteilungen der Österreichischen Bodenkundlichen Gesellschaft, Heft 74: 111-126.

Published Abstracts:

Huber K., K. Weckström & R. Schmidt (2008): Diatom-environment relationships in Alpine lakes and their application to climate reconstruction. 20th International Diatom Meeting, Dubrovnik 2008, Abstract Book: 54.

Schmidt R., K. Huber, K. Weckström & R. Klee (2008): The *Cyclotella comensis* complex in alpine and pre-alpine lakes. 2nd Central European Diatom Meeting (CEDIATOM2), Trento 2008, Abstract Book: 85.

Huber K., R. Klee & R. Schmidt (2007): Distribution and morphological variability of *Cyclotella*-taxa in the late glacial of Längsee (Austria). 1st Central European Diatom Meeting, Berlin 2007, Abstract Book: 28.

Oral presentations:

24.10.2008
Huber K., K. Weckström & R. Schmidt: Late glacial climate development inferred from diatoms (Längsee, Austria). 1st meeting of the Scientific Advisory Board, Institute for Limnology, Mondsee, Austria.

08.09.2008
Huber K., K. Weckström & R. Schmidt: Diatom-environment relationships in Alpine lakes and their application to climate reconstruction. 20th International Diatom Meeting, Dubrovnik, Croatia.

10.03.2008
Huber K., R. Schmidt & K. Weckström: Quantitative climatic and environmental reconstructions of Längsee from siliceous algae. CLIMATE CHANGE IN AUSTRIA DURING THE PAST 20,000 YEARS - linking climatic and environmental data from different archives, proxies and time scales (PALDAT) – Workshop, Institute for Limnology, Mondsee, Austria.

14.12.2007
Huber K.: Quantitative reconstructions of climatic and environmental variables by calibrated indicator organisms – A multi proxy study. Ph.D. Seminar, Paris Lodron University Salzburg, Austria

14.06.2007
Huber K. & R. Schmidt: Climatic and environmental reconstructions of the past 20,000 years with the example of two Austrian lakes. Palaeoecology Workshop: From Modern to Ancient Lakes, Institute for Limnology, Mondsee, Austria

24.03.2007
Huber K., R. Klee & R. Schmidt: Distribution and morphological variability of *Cyclotella*-taxa in the late glacial of Längsee (Austria). 1st Central European Diatom Meeting 2007, Freie Universität Berlin, Germany

19.03.2007
Huber K. & R. Schmidt: Möglichkeiten der Klima- und Umweltrekonstruktion. Sitzung des Kuratoriums der Österreichischen Akademie der Wissenschaften, Institute for Limnology, Mondsee, Austria

Poster presentations:

24.10.2008
Huber K., K. Weckström & R. Schmidt: The *Cyclotella comensis* complex in recent (pre-) alpine lakes and in a late glacial sediment core. 1st meeting of the Scientific Advisory Board, Institute for Limnology, Mondsee, Austria.

12.06.2008
Schmidt R., K. Huber, K. Weckström & R. Klee: The *Cyclotella comensis* complex in alpine and pre-alpine lakes. 2nd Central European Diatom Meeting, Trento, Italy

17.05.2008
Huber K., K. Weckström & R. Schmidt: Tracking late Pleistocene climatic variations in an alpine lake sediment core. 1st MySIL Meeting, Lunz am See, Austria

10.05.2007
Huber K., T. Peer, A. Tschaikner, R. Türk & J.P. Gruber: Importance of biological soil crusts for soil development in alpine ecosystems. Jahrestagung der Österreichischen Bodenkundlichen Gesellschaft, Seitenstetten, Austria