A 1000-yr record of environmental change in NE China indicated by diatom assemblages from maar lake Erlongwan

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ABSTRACT

Past environmental changes based on diatom relative abundances have been inferred from the maar Lake Erlongwan in northeast China. The limnology of Lake Erlongwan is affected by the strongly seasonal regional climate. The composition of diatom assemblages, in turn, responds to changes in the seasonal duration of ice cover in winter, water-column turnover in spring and autumn, and thermal stratification in summer. Statistical analysis of the sedimentary diatom assemblages reveals three significant stratigraphic zones over the past 1000 yr. The highest abundance of the planktonic species *Discostella* species occurs between AD 1050 and 1400 and suggests an annual ice-free period of long duration and well-developed summer stratification of the water column. This planktonic diatom peak between ca. AD 1150 and 1200 suggests that this period was the warmest over the past 1000 yr. The interval between AD 1400 and 1800 is marked by a decline in planktonic diatoms and suggests shorter duration of the ice-free season, weaker water stratification and possibly generally cold conditions. After AD 1800 relative abundances of planktonic diatoms, including *Puncticulata praetermissa* and *Asterionella formosa*, increase again, which indicates lengthening of the duration of the annual ice-free period and a stronger overturn of the water column. All these data imply that the pattern of the seasons is different between the MWP and the 20th century.

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Introduction

Lakes are excellent sensors of environmental change, and lake sediments can provide well-resolved records of change on different time scales. Although human activities in lake catchments can cause problems of interpretation, it is evident that lake ecosystems respond sensitively to climate variability and that these responses are registered in lake sediments (Battarbee, 2000). Crater and maar lakes are especially sensitive to climate change because typically they have a small catchment area and limited inflow/outflow. Moreover, they often provide high-resolution records due to limnological processes favorable to the development and preservation of seasonally laminated sediments (Zolitschka et al., 2000).

Among the biological proxies found in lake sediments, diatoms are excellent indicators of environmental conditions and have been widely used to reconstruct Holocene climate variability (Smol and Cumming, 2000; Battarbee et al., 2001; Mackay et al., 2003b). Furthermore, numerous studies on lake systems have shown that seasonal changes in the composition, production and diversity of diatom communities are related to variations in limnological processes such as the duration and timing of ice cover in winter, the stability of the water column, thermal stratification in summer and the strength of turbulent mixing associated with spring and autumn overturn (Pilskaln and Johnson, 1991; Weyhenmeyer et al., 1999; Lotter and Bigler, 2000; Mackay et al., 2003a; Tolotti et al., 2007). Recently, many studies have focused on sedimentary changes in diatom assemblages associated with global warming. A synthesis of over 200 diatom-based paleolimnological records, from the temperate zone to the Arctic, reveals remarkably similar diatom shifts across the Northern Hemisphere since the 19th century (Smol et al., 2005; Rühland et al., 2008). In high latitudes, subarctic lakes as well as in non-enriched, non-acidified temperate lakes, a rise in temperature associated with global warming appears to significantly alter the composition of diatom communities by its effects on the duration of the ice-free season and that of the thermal stratification of the water column. In the sediment records, this is expressed by an increase in the relative abundances of planktonic diatoms (Smol et al., 2005; Rühland et al., 2008). Rühland et al. (2010) also reported that in several dimictic, temperate lakes, some of which had been affected by cultural eutrophication, pinnate planktonic diatoms such as *Asterionella formosa* and *Fragilaria crotonensis* commonly associated with moderately

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enriched waters had recently increased in relative abundance. These particular planktonic diatoms had increased despite recent declines in measured nutrient such as total phosphorus (TP), suggesting that this may be a response to recent increases in temperature compounded by an already moderately enriched water column.

The climate of northeast (NE) China is controlled by the East Asian monsoon system and is strongly seasonal; monthly mean temperature ranges between $-20°C$ and $+20°C$. The limnology of the lakes in NE China is in turn strongly affected by prevailing climatic conditions. During winter, the region is dry, very cold and lakes are ice-covered from the middle of November to the end of the following April (Chu et al., 2005). Strong northerly winds are common in the spring season and promote the mixing of the water column. During summer, the region is warm and lakes are thermally stratified. Summers are also very moist as 85% of the annual precipitation falls between April and September (Chu et al., 2005). This rain contributes to the replenishment of the pool of nutrients, especially silicon, during autumn overturn.

Historical documents testify that very few humans lived in NE China prior to AD 1860 (Editorial Board for flora of China, 1995). It has only been since AD 1861 that the government of the Qin dynasty repealed the command that previously forbade people to settle there, and human populations since that time have rapidly increased. Thus, it seems reasonable to conclude that regional human impact on landscapes before the 20th century was negligible but impact likely increased after AD 1861. Furthermore, the Japanese invasion of NE China led to a phase of regional forest clearance. This is confirmed by pollen records that show minimum values of *Pinus* and maximum values of *Artemisia* between AD 1930 and 1940 (Mingram et al., 2004).

Material and methods

There are 8 maar lakes in the Long Gang Volcanic Field (LGVF) region, located in Jilin Province, NE China. Geochemical and pollen analyses have already been published from two of these lakes, Xiaolongwan and Sihailongwan (Mingram et al., 2004; Schettler et al., 2006; Chu et al., 2009). Our study focuses on Lake Erlongwan (EML) (42°18′N, 126°21′E), a dimictic lake that occupies an area of ca. 0.3 km² at 724 m.a.s.l. (Fig. 1). It is a closed lake with a small catchment (0.4 km²) with no natural inflows or outflow (Mingram et al., 2004). Currently, the trophic status of Erlongwan is oligotrophic (mean concentration values for TP, TN and dissolved silica are 12, 400

and 80 μg/L, respectively). At the end of the summer season the stratification of the water column is well marked in both the temperature and dissolved oxygen profiles (Mingram et al., 2004).

In 2001, a 66.5-cm-long sediment core was retrieved from the central, deepest region of the lake using a UWITEC gravity corer at a water depth of 36 m. From 0 to 50 cm core depth, the sediment was laminated. Below that, between 51 cm and 66.5 cm core depth, sediments were composed of a graded layer. This correlates with the graded layer that characterizes the upper sediments of the long piston core, ERL-B, studied by Frank (2007). Here, we report strictly on the laminated record of the top 50 cm as it is assumed that such graded layers formed rapidly as a result of a sediment slump (Frank, 2007). An age model was developed using radiometric ^{210}Pb, ^{137}Cs and ^{14}C analyses (Fig. 2). The activities of ^{137}Cs, ^{210}Pb, and ^{226}Ra were measured by gamma spectrometry using a low-background well-type germanium detector (EGPC 100P-15R) at the Institute of Geology and Geophysics, Chinese Academy of Science, Beijing. The counting errors were less than 5% and 3% for ^{210}Pb and ^{137}Cs, respectively. Radiometric dates were calculated using the constant rate of supply (CRS) ^{210}Pb dating model (Appleby and Oldfield, 1978; Appleby et al., 1986) and validated using the ^{137}Cs stratigraphic record, notably the 1963 peak that corresponds with the maximum fallout from atmospheric testing of nuclear weapons (Appleby, 2001; Jha et al., 2003). A *Pinus* macrofossil taken at 49.5 cm core depth was dated by AMS ^{14}C at the Poznan Radiocarbon Laboratory. The radiocarbon date was calibrated using the OxCal 4.1 program and the IntCal09 radiocarbon calibration curve (Bronk Ramsey, 2009).

The final age–depth model was developed by combining results of the ^{210}Pb and ^{14}C dating techniques (Fig. 2). Concentration in ^{210}Pb decreases at the top of the core and this indicates a recent increase in sediment rate, possibly linked to catchment disturbances such as the building of a road that runs along the northern shoreline of the lake in the 1970s. Our results are also consistent with the chronology developed for a different core but using a combination of varve-counting and $^{137}Cs/^{210}Pb$ radiometric analyses (You et al., 2008). The AMS date (Poz-19967) based on the *Pinus* macrofossil yielded a date of 1045 ± 30 ^{14}C yr BP (Fig. 2), which after calibration gave an age range of AD 900–1030. The ages of the samples below those dated with ^{210}Pb and above the radiocarbon date at 49.5 cm were linearly interpolated. Furthermore, linear extrapolation was used to extend the age-model to the base of the core at AD 980 (Fig. 2). The pollen record over the 1000 yr from our short core (data not shown) is very similar to the one from Sihailongwan (Mingram et al., 2004). This
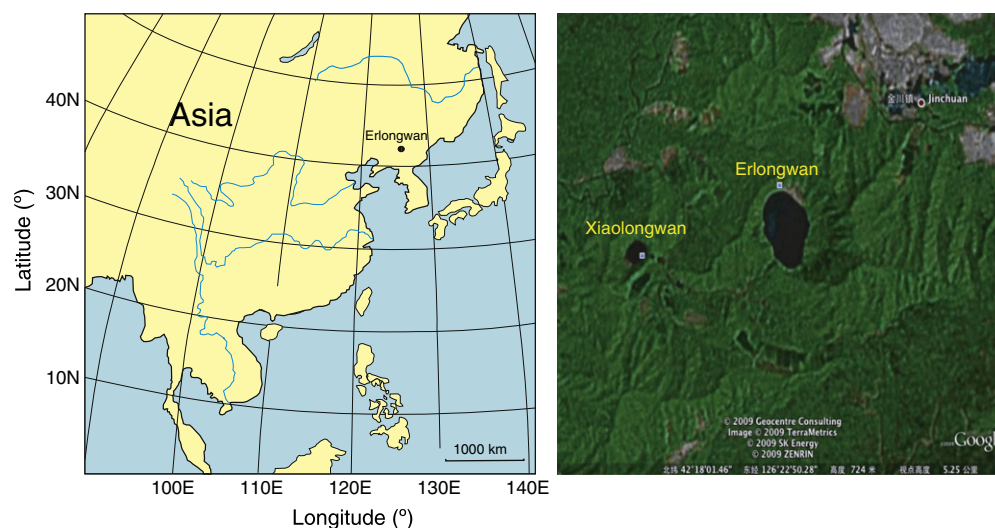

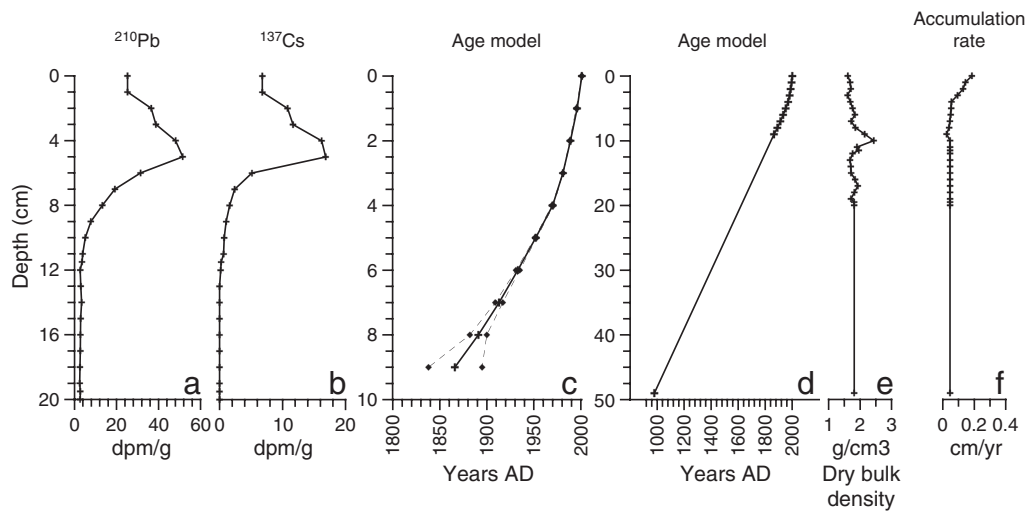**Figure 1.** Location of the Erlongwan maar lake (EML).

Figure 2. The EML short core ^{137}CS–$^{210}Pb_{ex}$ age model diagram. a-b. concentration of ^{210}Pb and ^{137}Cs. c-d. ^{210}Pb, ^{137}Cs and ^{14}C age model. e. density of sediment. f. Sediment accumulation rate.

suggests that the two age models, this one and the one based on varve-counting from Lake Sihailongwan, are consistent.

Diatom samples were prepared in test tubes from approximately 0.1 g of dry sediment using hot H_2O_2 followed by HCl to remove organic matter and carbonates respectively (Battarbee et al., 2001; Li et al., 2009). Diatom concentrations (valves/g) were calculated by the addition of divinylbenzene microspheres (Battarbee and Kneen, 1982). Diatom taxonomy followed the guidelines of Krammer and Lange-Bertalot (1986–1991), although more recent works such as Tanaka (2007) was also used, especially for centric diatoms belonging to *Discostella* and *Puncticulata*, two genera recently separated from *Cyclotella sensu lato*. Valves were identified to the lowest taxonomic level possible. However, we chose to merge *Discostella pseudostelligera*, *Discostella woltereckii* and *Discostella stelligera* into "*Discostella* species" because these three taxa were difficult to distinguish consistently under light microscopy (Haworth and Hurley, 1984; Tanaka, 2007). For each sample at least 400 – 600 valves were counted using oil immersion phase-contrast light microscopy at ×1000 magnification. The diatom data are displayed as percent relative abundances. Biovolumes of the dominant planktonic diatoms were determined following the guidelines by Hillebrand et al. (1999) (Table 1). The biovolumes were then multiplied by the diatom concentration, the dry bulk density and the sedimentation rate to derive the biovolume accumulation rate (BVAR) for each of the dominant planktonics. BVAR are expressed in $\mu m^3\,cm^{-2}\,yr^{-1}$.

Stratigraphic diagrams were constructed using C2 version 1.5.1 (Juggins, 2007). Diatom zones were delimited by optimal partitioning (Birks and Gordon, 1985) using the unpublished program ZONE (version 1.2) (Lotter and Juggins, unpublished software, 1994). Statistically significant zones were determined using BSTICK (Birks and Line, unpublished program) based on the broken-stick approach (Bennett, 1996).

Table 1
Cell biovolume for the dominant taxa found in the surface -sediment of Lake Erlongwan.

Taxon	Median length/diameter	n	Cell biovolume (μm^3)
Discostella species	4.9	50	45
P. praetermissa	12.2	20	710
A. formosa	54.5	20	330
F. nanana	65.6	20	400
S. acus	103.5	8	660

Detrended correspondence analysis (DCA) was undertaken on a reduced dataset of diatom species (those with >1% relative abundance in any one sample) to establish the magnitude of species turnover over the last millennium. Relative abundance data were square-root transformed in order to stabilize species variance and rare species were down-weighted. An axis 1 gradient length of 1.760 standard deviation (SD) units indicated that the linear ordination technique of principal components analysis (PCA) was appropriate for subsequent analysis (Leps and Smilauer, 2003). For PCA, only 19 taxa were included in the analysis as a more rigorous screening criterion was employed than for DCA (taxa were also deleted unless they occurred in any given sample with an abundance of at least 2%). Relative abundance data were square-root transformed. Ordination analyses were undertaken using Canoco version 4.5 (ter Braak and Smilauer, 2002).

Several diatom calibration datasets have been developed from Chinese and Mongolian lakes. The datasets from Tibet (Yang et al., 2003) and Mongolia (Shinneman et al., 2009) were designed to span salinity gradients and both are dominated by brackish species, while the dataset developed from the Yangtze River floodplain (Yang et al., 2008) is focused on shallow eutrophic to hypertrophic lakes. Thus at present, there is no diatom dataset available that would be suitable to infer past water chemistry for a deep, oligotrophic lake from NE China, such as Lake Erlongwan. Some auto-ecological information is available, however, thanks to the lake monitoring and sampling of contemporary diatom habitats of the neighboring Lake Sihailongwan, which is another maar lake in LGVF, with similar water chemistry and morphometry to Lake Erlongwan (Chu et al., 2005; Rioual et al., 2009).

Diatoms are generally not known to be very sensitive to water temperature, as shown by culture studies (Butterwick et al., 2005) as well as from observations of live populations. For example, Stoermer and Ladewski (1976) showed that most planktonic diatoms, including species such as *A. formosa* and *D. pseudostelligera* which are abundant in Erlongwan, are capable of sustained growth within a wide temperature range (5–25°C). However, climate affects the physical properties of the lake water column, especially as it controls the seasonal durations of ice cover, water column mixing and stratification, which all have profound effects on the availability of nutrients and light necessary for algal photosynthesis and growth. Thus, climate has an indirect influence on the composition and productivity of phytoplankton, especially non-motile organisms such as diatoms. Therefore in this paper, we undertake a detailed qualitative paleolimnological interpretation of
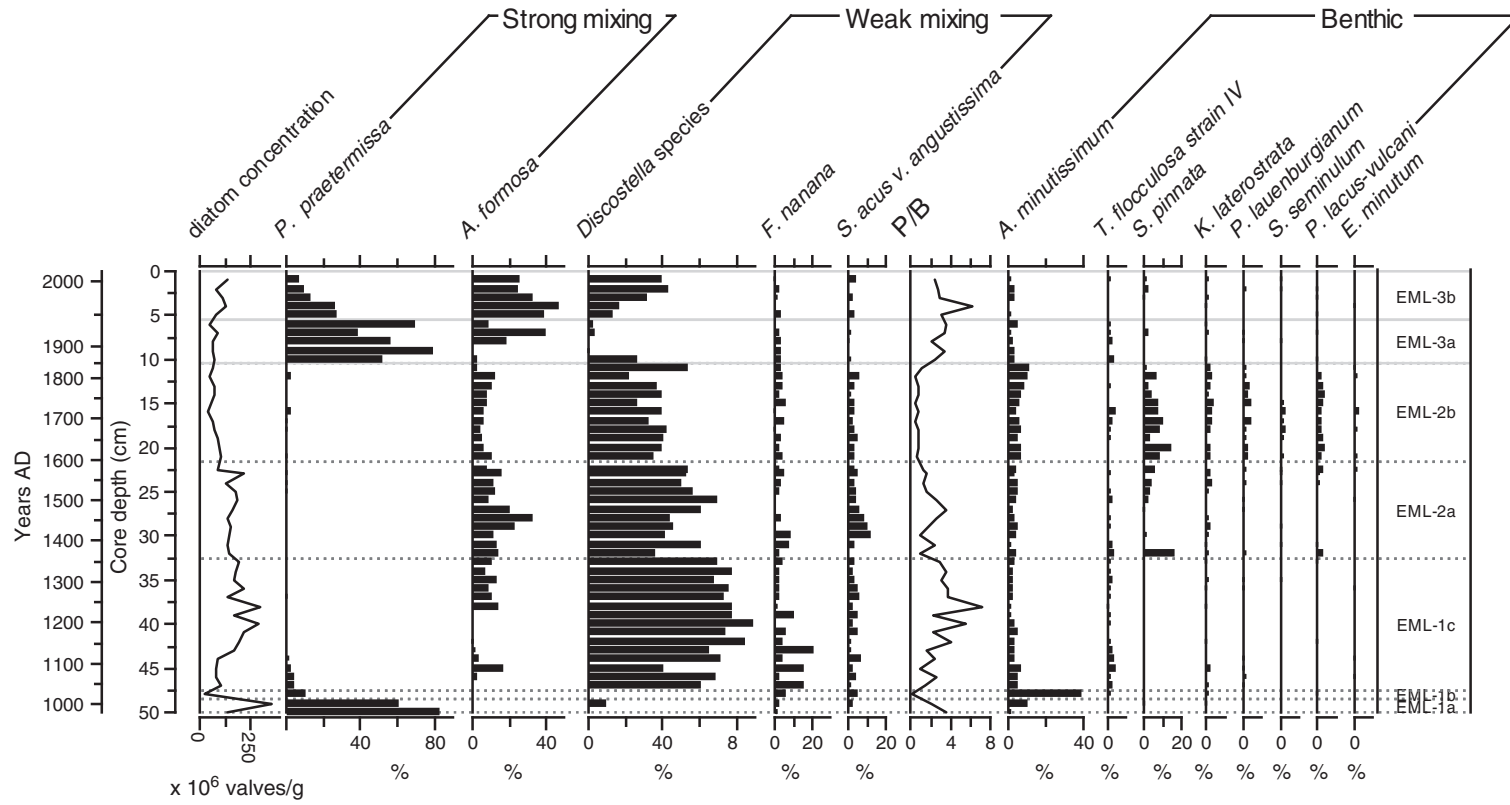
Figure 3. The EML diatom record of the past 1000 yr. Only major species are plotted. P/B is the ratio of planktonic to benthic diatoms. Diatom concentrations ($\times 10^6$ valves/g) are plotted on the left hand-side.

the Lake Erlongwan sediment sequence based mainly on the growing body of literature that focuses on the ecology of planktonic diatoms, especially their responses to climate-driven changes in limnology.

Results and discussion

Lake Erlongwan diatom stratigraphy

We identified 189 diatom species in the sediments from the Lake Erlongwan (Fig. 3). Three significant zones were recognized by optimal partitioning of the diatom data. In addition, we also distinguished subzones (Fig. 3). Although the chronology developed for our core is not robust enough to discuss the changes that occurred on a decadal time scale, it still allows for an interpretation of the changes that occurred on a centennial time scale over the last 1000 yr.

Puncticulata praetermissa largely dominates the early part of the record (EML-1a, AD 980–1010), both in terms of relative abundance and planktonic BVAR (13,900 $\mu m^3\, cm^{-2}\, yr^{-1}$) (Figs. 3 and 4). *P. praetermissa* is not often discussed in the literature, but taxonomic revisions of the *Cyclotella* species that have been transferred to the recently created genus *Puncticulata* (Håkansson, 2002), suggest that many of the records of the closely related species *Cyclotella comta* and *Cyclotella radiosa* belong in fact to *P. praetermissa* (Tanaka, 2007). These 'Cyclotella' species are reported to bloom preferentially in late summer at the onset of the autumn circulation period (Stoermer and Ladewski, 1976; Battarbee, 1981; Morabito et al., 2002; Baier et al., 2004; Kienel et al., 2005). *Puncticulata* spp. are fairly large in size, indicating high sinking velocities (Diehl, 2002; Diehl et al., 2002; Ptacnik et al., 2003; Reynolds, 2006). In Lake Geneva, *Puncticulata radiosa* (synonym of *C. radiosa*) is an indicator species for the algal

group typical of the spring season and strong mixing of the water column (Rimet et al., 2009). In Lake Sihailongwan, located 7 km east from Lake Erlongwan, analyses of sediment trap samples collected between 2003 and 2007 show that *P. praetermissa* blooms seasonally in spring and in autumn, when windy conditions cause turnover and the water column is well mixed (Rioual et al., 2009). *Puncticulata* is heavily silicified, implying that high levels of silicon might be required for rapid growth of this diatom (Bradbury and Dieterich-Rurup, 1993). In the Alps, *P. praetermissa* is found in mesotrophic lakes (Wunsam et al., 1995) and in sediment sequences covering the 20th century it is associated with either the start of eutrophication or the beginning of oligotrophication (Alefs and Muller, 1999; Hausmann and Kienast, 2006) suggesting again a preference for mesotrophic conditions.

Dominance of *Puncticulata* in the Lake Erlongwan sequence therefore suggests strong mixing of the water column, promoting high turbulence and nutrient concentrations favorable for spring blooms of *Puncticulata*. High summer precipitation may have also contributed to the dominance of *Puncticulata* as it would promote late-summer and autumn blooms. In a maar lake such as Erlongwan, mainly fed by groundwater, high lake-water silicon is promoted by high precipitation. This is because rainfall percolates through the coarse, pyroclastic materials that compose the crater and cause the groundwater to be enriched in silicon, as shown by Schettler et al. (2006) for Lake Sihailongwan.

The following zone, EMl-1b, which includes only 1 sample, is marked by a sharp increase in *Achnanthidium minutissimum*, which results in peak benthic relative abundances (Fig. 3). This species is currently the dominant species in the epilithon of Lake Erlongwan. At this time, diatom concentration and flux are very low. This could suggest a small slump of sediments deposited from the shallow
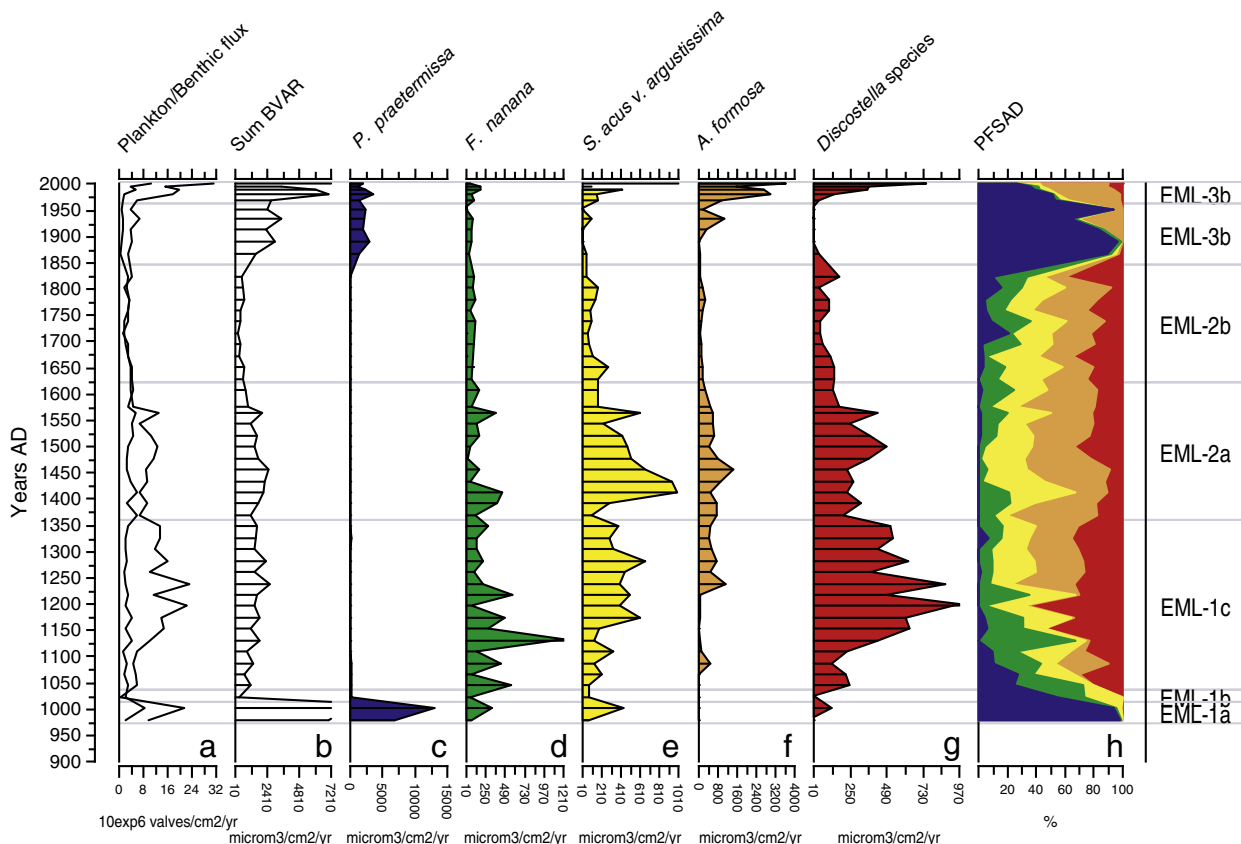

Figure 4. a. Planktonic and benthic diatom flux in the EML sediment record. b. Total diatom biovolume accumulation rate (BVAR). c–g. Variation in BVAR for the main diatom species (note the different scales on the x-axis). h. Contribution in terms of relative percentages to the total BVAR of the main diatom species.

littoral zone of the lake towards the center of the lake where the core was taken. Interestingly, *A. minutissimum* is also stimulated by increased silicon concentrations (Stenger-Kovács et al., 2006).

The start of EML-1c at ca. AD 1030 is marked by a dramatic shift in planktonic diatoms as *Discostella* species sharply increase while *P. praetermissa* gradually disappears from the assemblages (Fig. 3). Populations of *Discostella* species have been reported in a wide range of trophic conditions from oligotrophic to eutrophic lakes (Haworth and Hurley, 1984; Wunsam et al., 1995; Houk et al., 2010), and can also develop in response to eutrophication (Gregory and Oerlemans, 1998). In their studies on the microstratigraphy of annually laminated sediment from Finnish lakes, Battarbee (1981) and Simola (1977) found populations of *Discostella* growing all-year-round. In Lake Sihailongwan *Discostella* species, while it is also present in the water column year-round, is the only planktonic diatom to persist in abundance in the water column throughout summer thermal stratification (Rioual et al., 2009). Wang et al. (2008, 2012) also showed from Huguang Maar Lake in southern China that although small *Discostella* species persist in abundance in the water column throughout the year, they are most abundant during summer when the water column is thermally stratified (Wang et al., 2008, 2012).

In general, *Discostella* species like the other small-cell *Cyclotella sensu lato* have very low sinking velocities (about 0.5 m d^{-1}) (Ptacnik et al., 2003) and have consistently been found forming large populations in the deep chlorophyll layer that develops at the bottom of the epilimnion during summer thermal stratification in large oligotrophic lakes (Fahnenstiel and Glime, 1983). In contrast with large-size species affected by sinking (e.g., *Puncticulata*), these small diatoms are able to remain suspended within the warm water below the lake surface (Tolotti et al., 2007). Regarding their nutrient requirements, Tolotti et al. (2007) have shown from populations in Lake Tovel (a temperate lake of Italy) that small-sized *Cyclotella sensu lato* are better at exploiting low concentration of nutrients (in this case nitrate and silica) and better at remaining suspended within the warmer metalimnion beneath the lake surface in comparison with other diatoms such as *Fragilaria nanana*. Winder and Hunter (2008) have also argued that these small-size species undertake rapid nutrient uptake due to their large surface to volume ratio. The performance of individual phytoplankton species is strongly governed by the impact of thermal stratification on vertical mixing of the water column. Small-sized diatoms in particular, increased in abundance with reduced mixing, suggesting that suppressed turbulence gives them a competitive advantage over large-size diatoms (Winder and Hunter, 2008).

Two other planktonic species, *F. nanana* at the bottom and *A. formosa* at the top of EML-1c, are also common (Fig. 3) and make large contributions to the total BVAR (Fig. 4). *F. nanana* is generally associated with spring and autumn blooms (Simola, 1984; Simola et al., 1990; Interlandi and Kilham, 1999) although *F. nanana* has also been found associated with the summer season (St Jacques et al., 2009). *F. nanana* is particularly effective at competing for phosphorus, but is a poor competitor for silicon, and is thus typical of high Si:P ratios (Sommer, 1983). Bradbury and Dieterich-Rurup (1993) showed that in Minnesota (USA) *F. nanana* (called *Synedra nana* in that study) characterizes dilute lakes that often fail to circulate every year. When this happens, phosphorus remains in the bottom waters and in the anoxic sediments and becomes very limiting, which favors species like *F. nanana*. Collectively, these observations suggest that the presence of *F. nanana* can be indicative of periods of generally weak water column mixing.

In contrast, detailed experimental studies in oligotrophic lakes showed that *A. formosa* is abundant under conditions with high water turbulence (Morabito et al., 2002; Ptacnik et al., 2003) and therefore it is most often described as a spring-blooming species (Simola et al., 1990; Neale et al., 1991; Talling, 1993; Maberly et al., 1994) which

reaches its seasonal population maximum just at the onset of water column stratification (Reynolds, 1982). Stratification is the major factor ending the growth of *A. formosa* because it causes phosphorus limitation, photo-inhibition and enhanced sedimentation (this diatom has a relatively high sinking velocity by comparison with *Discostella*) (Reynolds, 1982; Neale et al., 1991; Ptacnik et al., 2003). The nutrient requirements of *A. formosa* are not well-defined as this species, while being commonly reported in nutrient-enriched lakes in Europe and North America (Bradbury, 1975; Anderson et al., 1995; Hall et al., 1999), is also found in oligotrophic lakes (Smol et al., 2005; Solovieva et al., 2005; Enache et al., 2011). It has been shown that under the epithet of *A. formosa* are pooled together several ecotypes or even cryptic species that differ genetically and show different physiologies and morphologies (Happeywood and Hughes, 1980; Soudek and Robinson, 1983; Pappas and Stoermer, 2001; De Bruin et al., 2004).

From the above, the three taxa abundant in EML1c could all indicate anthropogenic disturbance. However, it is unlikely that human activities caused the shift in diatom assemblage we are observing in this case because the region was very scarcely populated until the middle of the 19th century. Moreover, the benthic component of the assemblages stayed unchanged (i.e., with *A. minutissimum* and *Tabellaria flocculosa* strain IV as dominant) and doesn't indicate changing water chemistry (nutrients). This suggests that the shift in planktonic diatoms was climate-driven and caused by changes in nutrients and light associated with the physical conditions in the water column.

With this in mind and from what we discussed above, the start of the zone when *F. nanana* dominates the BVAR would indicate particularly low phosphorus concentrations and weak mixing. The interval between AD 1150 and 1200 during which *Discostella* species dominate (Fig. 3), even in terms of BVAR (Fig. 4), would indicate particularly long and stable thermal stratification and therefore warm summers. When such conditions prevailed, sinking becomes an important limiting factor (Tolotti et al., 2007). During that period *Discostella* would have grown throughout the summer by occupying a deep-water niche while species like *F. nanana* and *A. formosa* may not have been able to remain in suspension because of their relatively high sinking velocity (Ptacnik et al., 2003). While EML-1a suggested that planktonic diatom peaks occurred during periods of strong spring and autumn turnover (Fig. 3), diatoms in EML-1c indicate weak mixing, followed by strong thermal summer stratification and generally more oligotrophic conditions. Tentatively, our diatom record may suggest that EML-1c (AD 1150–1200) was the warmest period over the past 1000 yr. Interestingly, Catalan et al. (2002) reported from Lake Rédo (Pyrenees, Spain) rapid and simultaneous increases in abundances of *D. pseudostelligera* and *F. nanana* that closely followed the increase in water temperature in late summer during the 20th century.

EML-2a (AD 1360–1620) is characterized by a decline in relative abundances in the *Discostella* species (Fig. 3). In terms of BVAR, *A. formosa* and *Synedra acus v. angustissima* dominated EML-2a with significant contributions of *Discostella* species and *F. nanana* (Fig. 4). In natural planktonic assemblages *S. acus* is generally found to bloom in spring and autumn under mesotrophic conditions (Devaux, 1975; Battarbee, 1981; Horn and Horn, 1993). According to nutrient competition experiments, *S. acus* should be one of the best competitors for phosphorus and silicon at low concentrations (Sommer, 1983). *S. acus* is also characterized by a relatively low sinking velocity by comparison with *A. formosa* (Ptacnik et al., 2003). The ecology of this taxon is therefore very similar with that of *F. nanana*. The assemblages of this zone would therefore suggest weaker summer stratification compared with the previous interval that was dominated by *Discostella* species.

The main feature of EML-2b (AD 1620–1840) is the increase in the relative abundances of a diverse benthic assemblage (Fig. 3). Simultaneously, there is a marked decrease in diatom BVAR and flux, especially

of planktonic taxa (Fig. 4). Common species in this zone include *Staurosirella pinnata*, *A. minutissimum*, *Psammothidium lauenburgianum*, *Psammothidium lacus-vulcani*, *Karayevia laterostrata*, *Sellaphora seminulum* and *Encyonema minutum*. Erlongwan is a deep lake with steep shorelines and a high aspect ratio (depth/diameter), typical for lakes formed by a volcanic eruption. In this type of lake the littoral area is very small as the rapidly increasing water depth limits the availability of light and therefore restricts the extent of benthic habitats inside the lake-basin. By contrast, the water column provides a large area for planktonic diatoms to develop that is little affected by changes in lake level. In Erlongwan, only a dramatic decrease in water level (by 25 m) would significantly decrease the area of the pelagic zone.

Pollen data for the region do not indicate any large change in precipitation occurred during this period (Mingram et al., 2004). It is therefore very unlikely that the shift in P/B ratio (the ratio of planktonic to benthic diatoms) observed in this zone was caused by a change in water level. On the other hand, temperature, because it controls the duration of ice cover and the length of the growing season is a very important factor influencing diatom productivity, especially for planktonic diatoms in the pelagic zone. The shortening of the growing season during cold periods would decrease the productivity of both planktonic and benthic diatoms, but its effect would be much more severe for the plankton.

In high-latitude lakes, in spring, ice cover starts to melt at the shorelines but a long-lasting ice platform may remain in the central part of the lake (Douglas and Smol, 1999). This restricts the development of planktonic communities but it allows plenty of suitable habitats for periphyton to develop in narrow ice-free moats along the littoral zone (Smol, 1983). Similar diatom shifts have been observed in more temperate lakes too. For example, in the Experimental Lakes Area (Ontario, Canada) high relative abundances of benthic diatoms also characterize the sediment record during the cold period that occurred in the 19th century (Enache et al., 2011). It is likely that a similar situation developed in NE China at that time, as this region and Ontario have a broadly similar continental climate.

It is also interesting to note that such benthic communities are often found in arctic and alpine lakes characterized by cold-water conditions and long periods of ice cover (Koinig et al., 2002). Direct gradient analysis distributions of individual taxa and species diversity measurements have indicated a strong correlation between diatom distributions and temperature in Finnish Lapland lakes (Weckstrom and Korhola, 2001). The relationship is so strong that if temperature does not have a direct influence, it must be very closely related with factors that do. In particular, the relative abundance of small periphytic diatoms of the genera (sensu lato) *Fragilaria*, *Achnanthes* and *Cymbella* was found to increase with increasing altitude and latitude and decreasing mean annual temperature (Weckstrom and Korhola, 2001). The reason for this is most likely due to the shorter growing season at high altitude and high-latitude lakes because of prolonged snow and ice cover (Lotter and Lemcke, 1999).

In EML-3a (AD 1840–1960), *P. praetermissa* returns to the assemblages in significant numbers for the first time in over 750 yr (Fig. 3), driving sharp increases in total planktonic BVAR. Such increases in planktonic diatoms are therefore congruent with a longer ice-free season. This zone is also characterized by a significant increase in relative abundance and BVAR of *A. formosa*. As discussed above, large planktonic diatoms such as *P. praetermissa* need enhanced mixing of the water column during spring and/or autumn. *A. formosa* also favors highly turbulent water due to its relatively high sinking velocity (Ptacnik et al., 2003). Therefore, the dominance of planktonic diatoms with high sinking velocity in this period indicates long duration of water overturn condition. Abundant *Puncticulata* would also indicate a large increase in silicon input to the lake. This could be linked with increase precipitation and/or with thawing of soils in the lake catchment at the end of the previous cold interval. Wet summers should result in low light conditions due to cloud cover, but with

increase runoff and nutrient loading from the catchment, particularly Si, therefore favoring high Si and low light species like *Puncticulata* (Kilham et al., 1996) while being less favorable to species such as *Discostella*, associated with stable thermal stratification.

In the sedimentary record from nearby Lake Sihailongwan, reconstructed pollen assemblages show that between AD 1900 and 1950 the relative abundance of *Pinus* pollen declined significantly, concomitant with increasing abundances in cereal-type pollen and *Artemisia*, which suggests human exploitation and an opening-up of regional landscapes (Mingram et al., 2004). This pollen record matches with the historical records of human activities in NE China. The pollen profile from Erlongwan (data not shown) also shows trends similar to that from Lake Sihailongwan (Mingram, et al., 2004). The relative abundance of *Pinus* reaches its minimum in the 1930s, which ties well with the Japanese invasion of northeastern China. During that time *Pinus koraiensis* trees were selectively cut and the logs were taken away to Japan (Liu, 1989).

The increase of the relative abundance of *P. praetermissa* and *A. formosa* (Fig. 3) at first appears to be concurrent with changes in the relative abundances of *Pinus* and *Artemisia*, indicating that these diatoms may have responded to human activities as well as climate warming. However, we observed abrupt changes in diatom assemblage at about ca. AD 1840 while the pollen data from lakes Sihailongwan (Mingram, et al., 2004) and Erlongwan (data not show) show a trend of gradually decreasing *Pinus*, starting around ca. AD 1900, which indicates a progressive disturbance of the landscape. Moreover, both *P. praetermissa* and *A. formosa* have been abundant prior to the change in pollen, which indicate that these species are not always associated with human disturbance. Therefore, while we cannot totally rule out that human activities had an impact on the diatom shift recorded in EML-3a, it is more likely that it was caused by the increased duration and intensity of turbulent mixing in spring and autumn.

The uppermost zone EML3b (AD 1960 to 2001) is characterized by a rapid increase in sediment accumulation rate. Increased erosion into the lake from catchment disturbance, associated with the building of a small road along the shore of the lake in the 1970s, is probably the cause for the observed increased influx in sediment. The concomitant increase in diatom flux and planktonic BVAR, with *A. formosa* as the main contributor (Fig. 4), is most likely a response to this disturbance. Deposition of nitrogen associated with atmospheric pollution has been linked to recent increases of *A. formosa* in the sediment records of remote mountain lakes of North America (Saros et al., 2003). However, it is unlikely that this process caused the increase of *A. formosa* observed in EML3b in the 1950s (Fig. 3), because *A. formosa* rose before the deposition of N became important and decreased in the 1980s despite continuing increase in atmospheric pollution.

Finally, the very top of the sequence (last 20 yr) is characterized by an increase in *Discostella* species (Fig. 3), which contribute ca. 10% of the total planktonic BVAR (Fig. 4). The increase in the relative abundance of small planktonic *Discostella* species and the concurrent decrease in large diatoms *Asterionella* and *Puncticulata* are consistent with increased temperatures leading to strong thermal stratification of the water column. The increase of *Discostella* (*Cyclotella*) with global warming has been reported in the recent sediments of numerous lakes throughout the Northern Hemisphere, including those in Arctic environments (Sorvari et al., 2002; Rühland et al., 2003; Smol et al., 2005) and those in lower latitude, temperate regions (Rühland et al., 2008; Rühland et al., 2010). This recent shift in diatom assemblage is also concurrent with the well-documented decrease in precipitation and cloud-cover in NE China, which is especially marked in the spring and summer seasons (Kaiser, 1998; Liu et al., 2005; Wang and Zhou, 2005; Piao et al., 2010). As discussed above, lower precipitation and cloud-cover would not only decrease silicon input to the lake (to the detriment of *Puncticulata* and *Asterionella*) but also promote strong thermal stratification favorable to *Discostella*. Another negative impact of climate warming on populations of *Asterionella* is that it reduces the
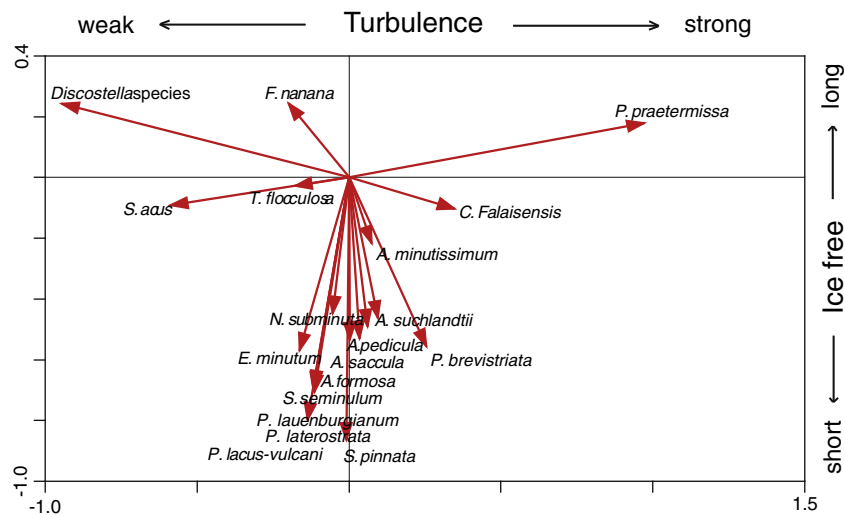
Figure 5. Principal component analysis of the EML diatom data. PCA axis-1 reflects a gradient of turbulence of the lake water column, and PCA axis-2 reflects the duration of the ice-free period.

period of time when *Asterionella* can grow without being infected by chytrid parasites (Ibelings et al., 2011). Furthermore, it is likely that the nutrient load to the lake has been reduced in the most recent past as the effects of the disturbance caused by road-building have receded. This could also have contributed to the decline in *Asterionella*, as this species requires a substantial supply of phosphorus to compete successfully (Horn et al., 2011). Interestingly, when comparing the top of the core with zone EML1c we can see that the percentages of *Discostella* have remained relatively low and that diatoms associated with spring/autumn turbulent mixing are still abundant. The current warming trend is therefore different from the previous warm period in

the way it is expressed in the diatom record. Difference in the relative length of the spring, summer and autumn seasons may be the cause of this difference.

Principal component analysis

PCA-axis 1 explains 55% of the variation in diatom assemblages at Erlongwan. *P. praetermissa* has a very high positive species score along this axis (0.970) while *Discostella* species and *S. acus* have species scores of −0.943 and −0.588, respectively. PCA-axis 1 therefore appears to represent a gradient of water column stratification/mixing (Fig. 5).
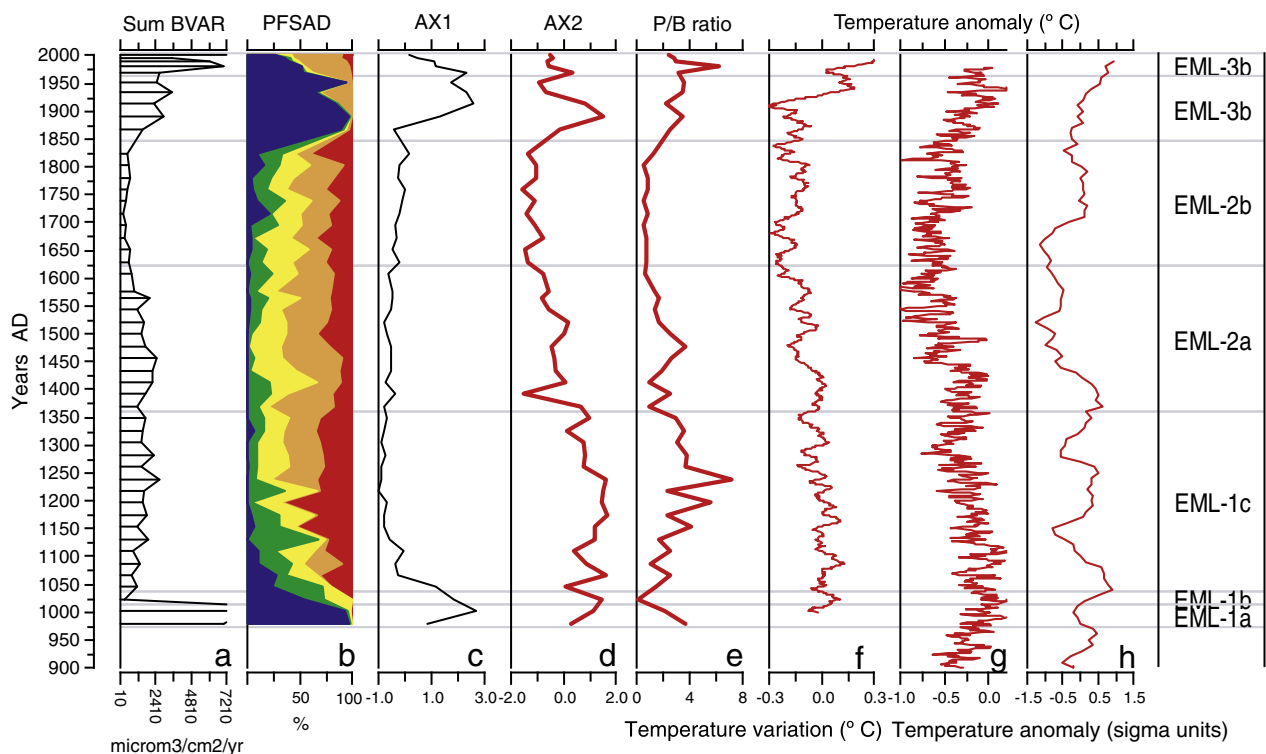

Figure 6. Comparison of the EML diatom record with temperature data for the Northern Hemisphere and China over the past 1000 yr. a. Diatom biovolume accumulation rate (BVAR) at EML; b. contribution of the main diatom species to the BVAR; c. sample scores on the PCA axis-1; d. sample scores for PCA axis-2; e. P/B ratio; f. temperature variation of the Northern Hemisphere (Crowley, 2000). g. Temperature anomaly for the Northern Hemisphere (Moberg et al., 2005). h. Temperature reconstruction for the whole of China (Yang et al., 2002).

Axis-2 explains less variation (11%) but several benthic taxa have highly negative species scores including *S. pinnata* (-0.861), *P. lacus-vulcani* (-0.797), *P. laueburgianum* (-0.699), *K. laterostrata* (-0.702), *S. seminulum* (-0.692) and *E. minutum* (-0.568). *A. formosa* is also negatively associated with axis 2 (-0.532). Positive axis 2 species scores are only weakly associated with the planktonic taxa *F. nanana* (0.241), *Discostella* species (0.241) and *P. praetermissa* (0.180). PCA-axis 2 therefore represents change in the relative contribution of the benthic flora to the assemblages. This is confirmed by the curves for the sample scores on PCA-axis 2, which closely resemble the P/B ratio (Fig. 6). However, as seen above, this is mainly an indirect proxy record as high relative abundance of benthic species in Erlongwan reflects low productivity of planktonic diatoms. PCA-axis 2 may therefore represent the duration of the ice-free season (Fig. 5).

The diatom assemblages analyzed here, derived from a core taken in the deep zone of the lake, is largely dominated by planktonic diatoms and therefore mainly reflects changes in the pelagic zone of the lake. This explains why most of the variations in the diatom assemblages, as reflected by PCA axis-1, are related to the differences in ecology of the main planktonic species.

Comparison with Northern Hemisphere temperature records

Currently, there is no record of mean annual temperature changes from NE China covering the past 1000 yr with the same centennial-scale resolution as the diatom record from Erlongwan. We therefore compare the P/B ratio and PCA axis 2 sample scores with several multiproxy reconstructions of mean annual temperatures for other parts of China (Yang et al., 2002) and the entire Northern Hemisphere (Crowley, 2000; Moberg et al., 2005) (Fig. 6). The composite temperature index for China by Yang et al. (2002) is derived from various proxy records including ice-core, tree-ring, lake geochemical data and the $\delta^{18}O$ record from peat cellulose of Jinchuan, which is located near Lake Erlongwan.

In zones EML1 (a, b, c), high P/B ratio and high sample scores on PCA axis-2 characterize long ice-free season indicating a warm period. By contrast, zone EML2 (a,b), with low PCA axis-2 scores, corresponds with shorter ice-free season indicating a period of cold climate. In zone EML3a, high scores on PCA axis-2 indicate a return to warm conditions at ca. AD 1885. These three intervals correspond to the Medieval Warm Period, the Little Ice Age and the 20th century warming trends within dating uncertainties. The curve of PCA-axis 2 scores broadly matches with the temperature reconstruction of Crowley (2000) and Moberg et al. (2005), but the fit is not as good for the reconstructions of Yang et al. (2002) (Fig. 6).

Conclusions

In this study, we have presented diatom-based evidence from a lake in NE China for environmental and climatic changes over the past 1000 yr. The composition and abundance of diatom assemblages, especially the P/B ratio, reflect the relative lengths of the ice-cover and ice-free seasons, which are linked to changes in temperature. Three intervals were identified by their diatom assemblages and correspond within dating uncertainties to the Medieval Warm Period, the Little Ice Age and the 20th century warming trends. Consistent with other paleolimnological studies from maar lakes (Kienel et al., 2005; Rioual et al., 2007), the diatom assemblages from Erlongwan exhibit sensitive response to changes in seasonal conditions, and thus can be used as indicators of the circulation patterns of the lake, which are closely linked to climate. The diatom record suggests that the period between ca. AD 1150 and 1200 was the warmest interval of the past 1000 yr. The length of the seasons is also different between the MWP and the 20th century; during the MWP the duration of summer was longer while the spring and autumn were shorter than the 20th century. Finally, despite the fact that human activities had an

impact on Lake Erlongwan during the 20th century, diatom assemblages appear to respond to the most recent period warming, as has been observed in other diatom records in North America and Europe (Rühland et al., 2008).

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