Lateglacial and early Holocene climatic fluctuations recorded in the diatom flora of Xiaolongwan maar lake, NE China

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In recent years, many high-resolution palaeoclimatic records spanning the interval of global warming from the end of the Last Glacial Maximum to the start of the Holocene have been developed and investigated. This period of deglaciation is of particular interest because the climate was then characterized by several rapid changes and high variability, especially in the North Atlantic realm where these events are well recorded in ice, marine and terrestrial records (Shakun & Carlson 2010; Clark et al. 2012; Rasmussen et al. 2014).

In East Asia, the most detailed records of this period are provided by speleothems from central China (Wang et al. 2001; Liu et al. 2008, 2013; Ma et al. 2012; Zhang et al. 2014). There are also several lake and peat records of the Lateglacial period in East Asia, especially in northeastern China. However, conflicting interpretations have arisen from these records especially regarding the variations in monsoonal precipitation that have been inferred from the pollen and geochemical data. In particular, the statement of Hong et al. (2010, 2011) that the Younger Dryas period was wetter than the previous Lateglacial was refuted by Schettler (2011) and Stebich et al. (2011). In that context, it is useful to study more sites and different proxy records to improve our understanding of this period.

Lake Xiaolongwan is located in the Longgang Volcanic Field (LGVF), Jilin province, northeast China (Fig. 1). It is one of the eight maar lakes of the LGVF. Maar lakes are especially sensitive to climate change owing to their characteristic morphology such as a small catchment area and limited inflow/outflow (Marchetto et al. 2015). Moreover, they often provide seasonally laminated sediments that can be used to establish precise chronologies. Lake Xiaolongwan sediments therefore represent an excellent archive to decipher natural climate variability, as already demonstrated by previous studies (Chu et al. 2008, 2009, 2014; Sun et al. 2013; Xu et al. 2014). In particular, Xu et al. (2014) using pollen and Chu et al. (2014) using compound-specific carbon isotope analyses found significant periodicities in the Xiaolongwan Holocene sediment record that suggest a strong link between solar activity and temperature and monsoonal precipitation, respectively.

Changes in diatom species composition have been extensively used in palaeolimnological inferences of climatic and environmental change. Diatoms are outstanding indicators because they form a very diverse group of microscopic algae that are found in abundance in both planktonic and benthic habitats of lakes. Owing to their siliceous walls, they are generally well preserved in the sediment record. Therefore, diatom...
analysis of the sedimentary record can provide an insight into past environmental conditions within the lake itself. Moreover, because of their very short lifecycle, diatom assemblages can be considered to respond almost instantaneously to changes in the environment. The diatom record of Lake Xiaolongwan is also sensitive to environmental change, as shown by Panizzo et al. (2013) for the last 130 years. These authors found that the recent increase in planktonic diatoms was driven by changes in the duration of ice cover, the length of the growing season and/or increased dissolved organic carbon.

The primary aims of this study were to present the Lateglacial diatom record from Lake Xiaolongwan and use this record, in association with geochemical and physical data of the sediment, to assess the palaeoenvironmental evolution of this lake and provide new information on the regional climate development in northeastern China.

Study site and regional climate

Lake Xiaolongwan (latitude 42°18.0′N, longitude 126°21.5′E, altitude 655 m a.s.l.) is a small, closed maar lake with a maximum depth of 16 m and a catchment area of 0.16 km². Currently Lake Xiaolongwan is slightly acidic (pH = 6.5–6.9), with low electrical conductivity. It is mesotrophic with ranges for total phosphorus, total nitrogen and dissolved silica of 4–26 µg L⁻¹, 780–1820 µg L⁻¹ and 0.1–1.3 mg L⁻¹, respectively. It has relatively high dissolved organic carbon concentration (DOC, 2.4–12.3 mg L⁻¹; Rioual et al. 2013) and relatively low Secchi depth (2.1 m, as measured on 27th August 2014).

Present climate conditions are determined by the East Asian monsoon and are characterized by pronounced seasonality in temperature and precipitation. In summer, rainfall is mainly associated with the Southeast Asian summer monsoon and the Northeast Asian summer monsoon (Fig. 1). These cause warm and humid conditions during summer. The rainy season lasts from June to October and accounts for at least 60% of the mean annual precipitation of ~760 mm. In winter and spring, the Siberian High controls the strong winter monsoon winds, causes cold and dry climate conditions and creates favourable conditions for snow and dust storms. The ice-covered season lasts from the end of November until early April. The mean annual temperature for the period AD 1955–2005 was 3.2 °C (Chu et al. 2011). The vegetation

Fig. 1. A. Map showing the geographical location of Lake Xiaolongwan and selected elements of atmospheric circulation over East Asia. B. Aerial view of Xiaolongwan maar lake and its forested catchment. C. Bathymetric map showing the coring site (isobath intervals are in metres).
around Lake Xiaolongwan is a dense, mixed broadleaf/conifer forest dominated by Betula costata (Chu et al. 2014; Xu et al. 2014).

Material and methods

Sediment sampling and chronology development

In the late winter of 2006 when the lake was still ice covered, overlapping sediment cores were retrieved from a water depth of 14.5 m near the centre of the lake using a modified rod-operated piston corer. The core sections (diameter = 9 cm) were split in half longitudinally, with one half used for diatom and geochemical analyses sampled at 1-cm intervals, whereas the other half was used for making thin sections. For the preparation of thin sections, overlapping sediment slabs of 6.5 cm in length were cut off with a 1.5-cm overlap, then shock-frozen with nitrogen, vacuum-dried and impregnated with epoxy resin. Previous sediment trap experiments and independent radiometric dating have demonstrated the annual nature of the laminations observed in the sediment sequence of Lake Xiaolongwan (Chu et al. 2008). Varves were identified and counted from thin sections under a Leitz® polarizing microscope. The main types of varves that were identified in the sequence analysed were: clastic varves, dinocyst varves and chrysophyte cyst varves. Intermediate types of varve were also identified such as clastic-chrysophyte cyst, clastic-dinocyst, chrysophyte cyst-dinocyst varves (Fig. 5). It is important to note that diatom valves, because they are transparent and generally very small, cannot be seen at the magnification used to analyse thin sections. The varved sequence is continuous for the intervals 0–387 cm and below 415 cm. Between 387 and 415 cm, a slump interrupts the laminated sequence. In this paper, we focus on the bottom part of the sequence, below the slump.

In addition to varve counting, 25 radiocarbon ages were obtained from leaf and bulk samples and dated using the AMS 14C method (Table 1). All 14C ages were calibrated using the atmospheric data set from CALIB 4.0 (Stuiver et al. 1998). A detailed description of the age model based on varve counting has already been published for the upper 387 cm of the core (Chu et al. 2014). The floating varve-chronology for part of the core below the slump was anchored by using an AMS 14C date (11 298 cal. a BP, from leaf material).

Figure 2 shows that the varve chronology closely corresponds to the AMS 14C data from terrestrial plant macrofossils. The AMS 14C data from bulk samples seem to be older than from the macrofossils. This

Table 1. Radiocarbon ages from Lake Xiaolongwan.

<table>
<thead>
<tr>
<th>Lab code</th>
<th>Material</th>
<th>Depth (cm)</th>
<th>14C a BP (median)</th>
<th>Cal. a BP (range)</th>
<th>Laboratory</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>BA07706</td>
<td>Bulk</td>
<td>20</td>
<td>400±40</td>
<td>482</td>
<td>508–341</td>
<td>Peking University, China 1</td>
</tr>
<tr>
<td>BA07707</td>
<td>Leaf</td>
<td>56</td>
<td>1215±40</td>
<td>1156</td>
<td>1225–1063</td>
<td>Peking University 1</td>
</tr>
<tr>
<td>BA06527</td>
<td>Wood</td>
<td>107</td>
<td>1875±40</td>
<td>1822</td>
<td>1871–1736</td>
<td>Peking University 1</td>
</tr>
<tr>
<td>BA07708</td>
<td>Leaf</td>
<td>154</td>
<td>2615±40</td>
<td>2749</td>
<td>2760–2741</td>
<td>Peking University 1</td>
</tr>
<tr>
<td>BA07709</td>
<td>Leaf</td>
<td>165</td>
<td>2880±40</td>
<td>2979</td>
<td>3124–2948</td>
<td>Peking University 1</td>
</tr>
<tr>
<td>CG-4761</td>
<td>Bulk</td>
<td>186</td>
<td>3490±90</td>
<td>3757</td>
<td>3871–3639</td>
<td>Earthquake Institute, China 1</td>
</tr>
<tr>
<td>BA07710</td>
<td>Leaf</td>
<td>219</td>
<td>3850±40</td>
<td>4244</td>
<td>4350–4154</td>
<td>Peking University 1</td>
</tr>
<tr>
<td>CG-4762</td>
<td>Leaf</td>
<td>266</td>
<td>4780±80</td>
<td>5507</td>
<td>5597–5332</td>
<td>Earthquake Institute 1</td>
</tr>
<tr>
<td>BA07711</td>
<td>Leaf</td>
<td>280</td>
<td>4840±35</td>
<td>5592</td>
<td>5601–5493</td>
<td>Peking University 1</td>
</tr>
<tr>
<td>Poz-42550</td>
<td>Leaf</td>
<td>310</td>
<td>6230±35</td>
<td>7160</td>
<td>7232–7029</td>
<td>Poznan, Poland 1</td>
</tr>
<tr>
<td>Poz-47182</td>
<td>Leaf+charcoal</td>
<td>416</td>
<td>11 850±70</td>
<td>13 832</td>
<td>14 043–13 651</td>
<td>Poznan, Poland 2</td>
</tr>
<tr>
<td>Poz-47596</td>
<td>Leaf+charcoal</td>
<td>416</td>
<td>11 690±70</td>
<td>13 680</td>
<td>13 831–13 480</td>
<td>Poznan, Poland 2</td>
</tr>
<tr>
<td>Poz-42545</td>
<td>Leaf</td>
<td>424</td>
<td>11 680±100</td>
<td>13 687</td>
<td>13 832–13 468</td>
<td>Poznan, Poland 3</td>
</tr>
<tr>
<td>Poz-42553</td>
<td>Leaf</td>
<td>430</td>
<td>9960±0.50</td>
<td>11 298</td>
<td>11 548–11 241</td>
<td>Poznan, Poland 4</td>
</tr>
<tr>
<td>Poz-42554</td>
<td>Bulk</td>
<td>430</td>
<td>10 170±50</td>
<td>11 818</td>
<td>12 098–11 660</td>
<td>Poznan, Poland 4</td>
</tr>
<tr>
<td>Poz-47135</td>
<td>Leaf+charcoal</td>
<td>454</td>
<td>10 400±50</td>
<td>12 337</td>
<td>12 623–11 984</td>
<td>Poznan, Poland 4</td>
</tr>
<tr>
<td>BA07712</td>
<td>Leaf</td>
<td>506</td>
<td>11 120±55</td>
<td>13 137</td>
<td>13 166–13 005</td>
<td>Peking University 4</td>
</tr>
<tr>
<td>Poz-42549</td>
<td>Bulk</td>
<td>579</td>
<td>13 550±60</td>
<td>16 272</td>
<td>16 510–16 044</td>
<td>Poznan, Poland 4</td>
</tr>
<tr>
<td>BA07713</td>
<td>Leaf</td>
<td>606</td>
<td>14 485±80</td>
<td>17 348</td>
<td>17 618–17 092</td>
<td>Peking University 4</td>
</tr>
<tr>
<td>Poz-42546</td>
<td>Leaf</td>
<td>674</td>
<td>15 600±70</td>
<td>18 631</td>
<td>18 936–18 345</td>
<td>Poznan, Poland 4</td>
</tr>
<tr>
<td>Poz-42548</td>
<td>Bulk</td>
<td>674</td>
<td>16 320±80</td>
<td>19 459</td>
<td>19 783–19 148</td>
<td>Poznan, Poland 4</td>
</tr>
<tr>
<td>BA07714</td>
<td>Bulk</td>
<td>696</td>
<td>17 080±85</td>
<td>20 334</td>
<td>20 669–20 006</td>
<td>Peking University 4</td>
</tr>
<tr>
<td>Poz-42553</td>
<td>Bulk</td>
<td>754</td>
<td>17 260±80</td>
<td>20 541</td>
<td>20 876–20 213</td>
<td>Poznan, Poland 4</td>
</tr>
<tr>
<td>BA07715</td>
<td>Bulk</td>
<td>834</td>
<td>19 070±70</td>
<td>22 624</td>
<td>22 998–22 271</td>
<td>Peking University 4</td>
</tr>
<tr>
<td>Poz-42552</td>
<td>Bulk</td>
<td>845</td>
<td>17 760±80</td>
<td>21 116</td>
<td>21 459–20 784</td>
<td>Poznan, Poland 4</td>
</tr>
</tbody>
</table>

1Dates for the Holocene already published in Chu et al. (2014), not shown in Fig. 2.
2Dates obtained from samples within the sediment slump, excluded from the age model.
3Date excluded from the age model because of the low C content of the sample (~0.3 mg).
4Dates plotted on Fig. 2.
might be because of the lower reservoir effect associated with the macrofossil samples, or the presence of erosional material from catchment soil in the bulk samples. This is why we chose to use Poz-42553 (11 298 cal. a BP) instead of Poz-42554 (11 818 cal. a BP), which was taken at the same depth but from a bulk sample. Note that the date obtained at 424 cm, Poz-42545, from a macrofossil sample taken immediately below the sediment slump was not reliable because of the small amount of carbon available for dating. The error of the varve chronology is <4% for the past 9.0 ka BP and 6% for the past 10–20 ka BP. Figure 2 shows varve age and AMS$^14$C dating plotted against the sediment core depth.

**Geochemical analysis**

The water content and bulk density were calculated after freeze-drying and weighing each sample taken at 1-cm intervals. The concentrations of total organic carbon (TOC) and total nitrogen (TN) were analysed for freeze-dried subsamples. Details of the analytical method are given in Chu et al. (2009).

**Diatom analysis**

Diatom samples were prepared in test tubes from approximately 0.05 g freeze-dried sediment using hot $\text{H}_2\text{O}_2$ to remove organic matter (Renberg 1990). Diatom concentrations (valves g$^{-1}$ dry matter) were calculated by the addition of divinylbenzene microspheres (Battarbee & Kneen 1982). Subsamples of the homogenized suspension were diluted by adding distilled water and left to settle onto glass coverslips until dry. The coverslips were fixed onto glass slides with Naphrax$^\text{®}$. For most samples at least 300 valves were counted under an Olympus$^\text{®}$ light microscope using oil immersion phase-contrast at $\times1000$ magnification. In some samples from the Pleniglacial (before 15 ka BP) only 200 valves were counted owing to low diatom concentration and the high content of clastic material. Diatom identification and taxonomy were mainly based on Krammer & Lange-Bertalot (1986, 1988, 1991a, 1991b) but numerous taxonomic publications were also used to aid identification, principally for centric taxa such as Procházková et al. (2012) for *Discostella tatra*ca; Solak & Kulikovskiy (2013) for *Handmannia balatonis*; Scheffler & Morabito (2003) and Scheffler et al. (2005) for *Cyclotella comensis* morphotypes conminima and minima; and Edlund & Stoermer (1993) for *Urosolenia* resting spores. Biovolumes of the dominant planktonic diatoms were determined following the guidelines of Hillebrand et al. (1999) (Table 2). 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 planktonic diatoms (Wang et al. 2012). BVAR are expressed in $\mu$m$^3$ cm$^{-2}$ a$^{-1}$.

<table>
<thead>
<tr>
<th>Taxon</th>
<th>Valve length/diameter ($\mu$m)</th>
<th>n</th>
<th>Cell biovolume ($\mu$m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Asterionella formosa</em></td>
<td>30.6–68.0</td>
<td>45.8</td>
<td>46</td>
</tr>
<tr>
<td><em>Cyclotella comensis</em> mo. comensis</td>
<td>5.0–9.5</td>
<td>5.5</td>
<td>35</td>
</tr>
<tr>
<td><em>Cyclotella comensis</em> mo. minima</td>
<td>3.5–4.9</td>
<td>4.4</td>
<td>35</td>
</tr>
<tr>
<td><em>Discostella tatra</em>ca*</td>
<td>4.3–8.8</td>
<td>5.4</td>
<td>31</td>
</tr>
<tr>
<td><em>Fragilaria sp.</em></td>
<td>72–135</td>
<td>93.1</td>
<td>32</td>
</tr>
<tr>
<td><em>Handmannia balatonis</em></td>
<td>6.4–15.5</td>
<td>11.1</td>
<td>31</td>
</tr>
<tr>
<td><em>Stephanodiscus minutulus</em></td>
<td>7.1–9.2</td>
<td>8.1</td>
<td>30</td>
</tr>
<tr>
<td><em>Urosolenia</em> (resting spore)</td>
<td>2.9–11.8</td>
<td>6.2</td>
<td>35</td>
</tr>
</tbody>
</table>

^*The value given for *Urosolenia* corresponds to the biovolume of the resting spores only, not that of the vegetative cells as these were not preserved in the sediment.
Results

Diatom stratigraphy and varve analysis

Diatoms in the Lateglacial sediment of Lake Xiaolongwan are generally well preserved as the proportions of fragmented and/or dissolved valves were low. The diatom stratigraphy for the most common taxa identified in the 94 levels analysed is summarized in Fig. 3. The taxa are arranged in successional order and only the most abundant planktonic taxa are displayed along with the sum of benthic taxa. The diatom flux and BVAR are shown in Fig. 4 whereas the results of the varve analysis (varve types and thickness), the chrysophyte cyst flux and some geochemical data are presented in Fig. 5. Over the sequence investigated (10.6–19.7 ka BP), the 1-cm-thick samples represent between 14.5 and 53.5 years. On average a 1-cm sample represents 28.3 years of sedimentation. The time intervals between each sample analysed for diatoms range from 25 to 380 years, with an average of 97 years. After 15 ka BP, the maximum interval is 84 years with an average interval of 55 years between samples. Before 15 ka BP, the time resolution is much lower, with an average of 269 years between the analysed samples (range of 70–380 years).

Taxonomic remarks on the main diatom species

*Handmannia balatonis*. – *Cyclotella balatonis* Panticsek was considered a synonym of *Cyclotella radiosa* Grunow and/or *Cyclotella comta* (Ehrenberg) Kützing following the broad species concept that has been in use until recently for this group of centric diatoms (e.g. Krammer & Lange-Bertalot 1991a) (Supporting Information Fig. S1: 39–47). Using a more narrow species concept, Houk *et al.* (2010) re-instated *C. balatonis* as a valid species after investigating the type specimens. The group of species to which *C. balatonis* belongs was separated from *Cyclotella* by Håkansson (2002) who created for that purpose the genus *Puncticulata*. In a recent review paper, however, Khursevich & Kociolek (2012) re-instated the genus *Handmannia* that has been overlooked by Håkansson (2002). The transfer of the species *Cyclotella balatonis* to the genus *Handmannia* was carried out by Solak & Kulikovskiy (2013). Owing...
to this taxonomic confusion, there are few mentions of this species in the literature and knowledge on its distribution and ecology is very incomplete.

**Discostella tatrica.** – Like the other members of this recently erected genus, this species is difficult to identify consistently under a light microscope (Fig. S1: 1–7). In a previous study on Lake Xiaolongwan, Panizzo et al. (2013) identified this taxon as *Discostella woltereckii* (Hustedt) Houk & Klee. However, further analyses under a scanning electron microscope (SEM) revealed that this taxon is better identified as *D. tatrica*, a taxon recently described from lakes in the Tatra Mountain (Slovakia/Poland) by Procházková et al. (2012).

**Cyclotella comensis morphotypes comensis and minima.** – Following the work of Scheffler and colleagues (Scheffler & Morabito 2003, Scheffler et al. 2003, 2005), we distinguished two morphotypes of *C. comensis*: the nominal morphotype and the very small-sized morphotype *minima* (valve diameter 3.5–4.9 μm; Fig. S1: 8–14 and 15–31).

**Urosolenia sp., resting spores.** – As stated by Edlund & Stoermer (1993), diatom resting spores are often an overlooked and misconstrued component of siliceous microfossil assemblages (Fig. S1: 48–53). The spores from Lake Xiaolongwan varied in size from 2.9 to 11.8 μm in apical length and 3.1 to 6.7 μm in the perivalvar axis. The current taxonomy of this genus is extremely uncertain and we cannot attribute these spores to any described species.

**Fragilaria sp. 1.** – The ranges for valve length, width and stria density are 72–135 μm, 2.0–2.9 μm and 18.6–21.1 striae in 10 μm, respectively (Fig. S1: 61–63). The characteristics of this taxon are intermediate between those of *Fragilaria tenera* (W. Smith) Lange-Bertalot and *Fragilaria nanana* Lange-Bertalot as given in Hofmann et al. (2011).
Diatom, varve and geochemical analyses

The sequence was divided into six diatom assemblage zones. The results of the geochemical analyses are only briefly reported as a detailed interpretation of these data will be published elsewhere.

DAZ XLON-1, 740–585 cm, 19 730–15 620 a BP. –
This first zone can be subdivided into two subzones, mainly according to the percentages of *Cyclotella comensis* morphotype *minima*. The lowermost part of the sequence, DAZ XLON-1a from 19 730 to 17 040 a BP, is dominated by *Handmannia balatonis*, both in terms of relative percentage and planktonic BVAR. Owing to the large biovolume of this species, the average planktonic BVAR for XLON-1a is the largest of all the zones of the sequence (~800×10⁶ µm³ cm⁻² a⁻¹). The other abundant diatoms are *Urosolenia* resting spores, *Cyclotella comensis* morphotype *comensis* and *Discostella tatraica*. DAZ XLON-1b from 17 040 to 15 620 a BP is characterized by a sharp increase in the percentages of *Cyclotella comensis* m. *minima*, whereas those of *H. balatonis* decline. Although the average total diatom flux increases (~3.5×10⁶ valves cm⁻² a⁻¹), the small biovolume of morphotype *minima* causes a decrease in the average BVAR (~575×10⁶ µm³ cm⁻² a⁻¹). The varves are of the clastic type for the whole zone. The peak in chrysophyte flux between 18.3–17.8 ka BP corresponds to a high abundance of chrysophyte cysts of very small size (~9 µm in diameter) that could not be seen in the thin sections used to define the varve types. TOC and TN are low throughout XLON-1.

DAZ XLON-2, 585–546 cm, 15 620–14 310 a BP. –
DAZ XLON-2 is dominated by *D. tatraica* and can be divided into two subzones that are characterized by the subdominant species. In DAZ XLON-2a, from 15 620 to 14 780 a BP, *H. balatonis* is still abundant, whereas in DAZ XLON-2b from 14 780 to 14 310 a BP *Asterionella formosa* increases sharply. In DAZ XLON-2b, the averages for both the total diatom flux and the planktonic BVAR decrease, to ~2.4×10⁶ valves cm⁻² a⁻¹ and ~380×10⁶ µm³ cm⁻² a⁻¹, respectively. Varves in XLON-2a are of the clastic type, whereas in XLON-2b they are of the elastic-chrysophyte cysts.
type. XLON-2b is also characterized by a sharp increase in C:N ratio.

**DAZ XLON-3, 546–500 cm, 14 310–12 840 a BP.** – XLON-3 is dominated by *D. tatrica, A. formosa* and *Stephanodiscus minutulus*. The averages for both the total diatom flux and the planktonic BVAR increase to ~3.1×10^6 valves cm^-2 a^-1 and ~480×10^6 µm^3 cm^-2 a^-1, respectively. In XLON-3, all varves are of the clastic-dinocyst type.

**DAZ XLON-4, 500–484 cm, 12 840–12 490 a BP.** – The assemblages in this zone are almost exclusively composed of the two species *S. minutulus* and *D. tatrica*. *S. minutulus* is largely dominant (up to 76%). The averages for both the total diatom flux and the planktonic BVAR increase further, to ~3.7×10^6 valves cm^-2 a^-1 and ~565×10^6 µm^3 cm^-2 a^-1, respectively. This zone is also characterized by a sharp increase in varve thickness. All varves are of the clastic-chrysophyte cysts type.

**DAZ XLON-5, 484–427 cm, 12 490–11 170 a BP.** – The assemblages of this zone differ from that of the previous zone by the return of *A. formosa*. It can be divided into three subzones according to the fluctuations in the percentages of *D. tatrica* and *S. minutulus*. XLON-5a from 12 490 to 11 740 a BP is largely dominated by *D. tatrica*. In this subzone, the average total diatom flux increases but the average planktonic BVAR decreases and varves are of the clastic-chrysophyte cyst or the chrysophyte cyst-dinocyst types. XLON-5a is also characterized by an increase in the C:N ratio (Fig. 5). XLON-5b from 11 740 to 11 350 a BP is dominated by *S. minutulus*. This causes an increase of the average planktonic BVAR (~630×10^6 µm^3 cm^-2 a^-1), whereas the average total diatom flux remained constant at ~4.2×10^6 valves cm^-2 a^-1. In this subzone varves are of the clastic-chrysophyte cyst or chrysophyte cyst types. Chrysophyte cyst flux is the highest of the whole sequence. XLON-5c from 11 350 to 11 170 a BP, the percentages of *S. minutulus* collapse and the averages for both the total diatom flux and planktonic BVAR also decline. Varves are of the chrysophyte cyst or the chrysophyte cyst-dinocyst types. In XLON-5c TOC and TN values sharply increase.

**DAZ XLON-6, 427–414 cm, 11 170–10 690 a BP.** – The last zone is characterized by a collapse in the percentage of planktonic diatoms. Benthic diatoms represent over 90% of the assemblages in most samples of this zone. The averages for both the total diatom flux and planktonic BVAR drop to ~0.2×10^6 valves cm^-2 a^-1 and ~5×10^6 µm^3 cm^-2 a^-1, respectively. Varve thickness decreases sharply in the first part of this zone when the varves are of the chrysophyte cyst-dinocyst type. In the last three samples of the sequence, varves are of the dinocyst type and varve thickness increases. The C:N values increase.

**Discussion**

The changes in diatom assemblages are consistent with the ‘classic’ Lateglacial climate periods established in many records from the Northern Hemisphere. To make comparison easier, the terminology derived from the northern European pollen sequences such as Belling, Allerød and Younger Dryas, Rasmussen et al. (2014). In Fig. 5, the Xiaolongwan record is compared with the synchronized Greenland ice-core records, especially the GRIP record plotted with the GICC05modelext chronology (Rasmussen et al. 2014; Seierstad et al. 2014), with the Hulu cave speleothem record from central China (Wang et al. 2001), with the record of icerafted detrital carbonate from the North Atlantic that identifies times of Heinrich events H1 and H0 (Bond et al. 1999) and with the insolation at 50°N for June (Berger & Loutre 1991).

**The pleniglacial**

The geochemical analyses gave low values for total organic carbon (TOC) and total nitrogen (TN) for the pleniglacial part of the sediment core, whereas the thin sections revealed that the varves were mainly of the clastic type. Pollen analyses from the neighbouring Shailandong Lake indicate that at that time the vegetation was composed of taiga-like woodland patches, permafrost conditions were likely and the climate cold and dry (Stebich et al. 2009). It is also important to consider that the basin of Lake Xiaolongwan would have been 6–7 m deeper than it is nowadays. Thus, it is most likely that Lake Xiaolongwan was deep and oligotrophic as the supply of nutrients from the frozen catchment soils would have been limited. Nevertheless, the lake was not a substerile environment but already productive as indicated by the high BVAR values. This finding confirms the air-temperature reconstruction of Peterse et al. (2011) based on the paleosol-loess sequence from central China that indicated that deglacial warming started at 19 ka BP, i.e. 3000 years earlier than the strengthening of the East Asian summer monsoon. The onset of Northern Hemisphere deglaciation was also constrained at 19 ka BP by Clark et al. (2009), who drew their results from a very large data set of 14C and cosmogenic nuclide ages.

The first diatom subzone, XLON-1a (19 730–17 040 a BP) is characterized by high percentages and BVAR of *H. balatonis* (Figs 3, 4). Houk et al. (2010) reported this species as a pelagic diatom in mesotrophic to eutrophic lakes in Europe. Budzynska & Wojtal (2011) found it in abundance in a small, shallow, eutrophic lake in Poland where its maximum development is in
the winter–spring period and finishes with the onset of stratification. The same taxon is currently very abundant in Lake Sihailongwan, located a few kilometres away from Lake Xiaolongwan. In this deep (50 m maximum depth), clear-water, mesotrophic lake *H. balatonis* is most abundant in early spring (just after ice break-up) and in autumn when thermal stratification breaks down (P. Rioual, unpublished data). The other planktonic species that contribute significantly to the assemblages and BVAR are *Urosolena* spp., *Cyclotella comensis* in the lower part of the subzone and *Fragilaria* sp. and *D. tatrica* in the upper part of the subzone. *Urosolena* spp. are associated with clear, deep, base-poor lakes (Padisák et al. 2009) and with seasonal mixing of the water column (Souza et al. 2008), and therefore most probably have a seasonal distribution similar to that of *H. balatonis*. *C. comensis* morphotype *comensis* can be present in the water column throughout the year but reaches its peak during the summer period of thermal stratification (Scheffler et al. 2003). This species is more abundant in alkaline lakes with low phosphorus concentrations, moderate nitrate concentrations and a moderate mixing depth (Saros & Anderson 2015 and references therein).

Interestingly, between c. 18.5 and c. 17.3 ka BP *C. comensis* declines sharply (in percentages and BVAR), whereas the contribution of *Fragilaria* sp. 1 increases. Needle-shape planktonic araphid diatoms such as *Fragilaria tenceralanana* (previously included in the genus *Synedra*) are generally considered to have similar ecological requirements (Tolotti et al. 2007; Wang et al. 2012). In a temperate lake of the Italian Alps Tolotti et al. (2007) found that this type of *Fragilaria* species mostly develops from mid-summer to autumn. They also found a strong positive relationship between this taxon abundance and concentrations in nitrate–nitrogen and silica that were positively associated, in that lake, with high summer rainfall. It is well established that the wetter the climate, especially in humid, cool, temperate areas, the higher the amount of nitrogen supplied to the lake via terrestrial runoff and directly from precipitation (Clair & Ehrman 1996; Wetzel 2001; Kane et al. 2008). By causing nitrogen enrichment, wet summer conditions may therefore be more favourable to *Fragilaria* sp. 1 than to *C. comensis*. This assemblage shift occurs simultaneously with a significant increase in varve thickness and a peak in chrysophyte cysts. In their review of varves in lake sediments, Zolitschka et al. (2015) showed that in situations where vegetation and soils are not efficient for runoff control, varve thickness is highly correlated with variations in summer precipitation. Under such conditions, rainfall is transferred to the varves via enhanced sediment flux, resulting in thicker and more siliciclastic varves. Interestingly, this time interval corresponds to a strong East Asian Summer Monsoon event in the speleothem records of central China (Zhang et al. 2014).

The subzone XLON-1b (17 040–15 620 ka BP) is differentiated from XLON-1a by a significant decrease in the percentages and BVAR of *H. balatonis* and a shift in the proportions of the two different morphotypes of *C. comensis*. In XLON-1b, *C. comensis* morphotype *minima* is more abundant. Detailed investigations of the life cycle of these *Cyclotella* populations have confirmed that *C. comensis* fo. *minima* is a winter ecotype of *C. comensis* and that the morphological transition between the two occurs during sexual reproduction (Scheffler & Morabito, 2003; Scheffler et al. 2003). In alkaline lakes of northern Germany *C. comensis* fo. *minima* occurs in October in the plankton and blooms from January to March, whilst being completely absent from the plankton during the summer period. Therefore, XLON-1b suggests an interval with longer, colder winter periods. These conditions would delay and reduce the length of spring and would be favourable for *C. comensis* fo. *minima* to dominate the winter and early spring plankton whilst being detrimental to *H. balatonis*. The simultaneous increase in BVAR of *Fragilaria* sp. 1 also suggests weak spring circulation that may not have extended to the bottom of the lake and low phosphorus supply rates (Bradbury 1988). This is because *Fragilaria (Synedra)* species have consistently been found to be extremely good P-competitors (Sommer 1983; Grover 1988), having the lowest growth requirements for P of any species tested in culture (Kilham 1986). All together, these diatom shifts suggest that this interval of the Xiaolongwan record corresponds with a climate cooling event. Its timing overlaps with that of the ice-rafted debris event recorded in the North Atlantic at 17.0 ka BP (Heinrich event H1; Bond et al. 1999).

Zone XLON-2a (15 620–14 780 a BP) is characterized by the dominance of *D. tatrica* and the decreased relative abundance of *H. balatonis*. Simultaneously, the C:N ratio rose (Fig. 5), suggesting an increase in the input of organic matter from the catchment. TOC, however, did not increase significantly. In the Tatra Mountain lakes from where it was originally described, *D. tatrica* appears to be tolerant to different levels of nutrients as it was observed in ultra-oligotrophic to mesotrophic lakes (Procházková et al. 2012). Ecological information more relevant to our study is provided by sediment trap data from Lake Xiaolongwan (Chu et al. 2008; P. Rioual & G.Chu, unpublished data). The trap data show that *D. tatrica* is currently the most abundant planktonic species in the lake. It is abundant during the spring and autumn periods of turnover but is also present during summer stratification (P. Rioual, unpublished data). The relatively high DOC concentrations and low Secchi depth observed in recent years suggest that this small, wind-sheltered forest lake has a shallow mixing depth (Fee et al. 1996;
Von Einem & Granéli 2010). This shift from *H. balatoni*is to *D. tatrica* may therefore indicate a shallower mixing depth. This is consistent with the study of Saros et al. (2012), who observed a much lower mixing depth optimum for *Discostella* spp. than for *Handmannia* spp.

The last two diatom zones overlap with the ‘Mystery Interval’ (17.5–14.5 ka BP) that is characterized in the speleothem records of central China by a weak summer monsoon (Zhang et al. 2014).

**The Bolling – Allerød interstadial**

In their list of recommendations, Rasmussen et al. (2014) suggested that the Bolling – Allerød could be used as a non-archive-specific name for the generally mild climate period from approximately 14.6 to 12.9 ka BP. In the pollen record of Lake Sihailongwan, Stebich et al. (2009) determined that the interstadial lasted 1770 years, from 14 450 to 12 680 a BP. In the Xiaolongwan diatom record, the equivalent interval is found to have lasted a little longer, starting at c. 14.8 and ending at c. 12.8 ka BP, and to include two diatom zones.

The first of these, XLON-2b (14 780–14 310 a BP), is characterized by the sharp increase in *A. formosa* and the simultaneous collapse in *H. balatoni* (both in terms of relative percentages and BVAR). *A. formosa* is a definite spring species (Simola et al. 1999; Talling 1993; Salmaso et al. 2003) and a very good early indicator of nutrient enrichment, especially nitrogen. Consistent with the increase of the nitrophilous *A. formosa* (Saros et al. 2005; Michel et al. 2006; Hundey et al. 2014), there is a sharp rise in TN concentrations (Fig. 5). TOC concentrations also increase and suggest a general increase in lake productivity and in the input of organic matter from the catchment. Consistent with an increase in the productivity of the lake, the varve type changes from clastic to clastic-chrysophyte cysts.

The next zone, XLON-3 (14 310–12 840 a BP), is marked by further increase in TOC and TN concentrations in the sediment whereas the varve type changed to the clastic-dinocyst type. All these indicate a more productive lake system. Simultaneously, in the diatom assemblages *S. minutulus* and *A. formosa* expanded further whilst *H. balatoni* disappeared. Like *A. for-

*formosa*, *S. minutulus* is a typical late-winter and/or early spring-blooming species associated with cold water and low light conditions, when the water column is mixing (Druart et al. 1987; Kilham et al. 1996). These two species are reported to have higher requirements for nutrients than *Handmannia* and *Discostella* species. Their development indicates a longer and stronger spring period of mixing of the water column that extended to the sediment surface at the bottom of the lake and caused an increase in the rate of nutrient supply. Such long spring periods are associated with earlier break-up of the winter ice cover. Nutrient enrichment may have also been caused by higher water inflow and associated nutrient delivery. In the sediment record from Lake Sihailongwan, the increase in pollen production and the initial expansion of *Ulmus* and *Fraxinus* (Stebich et al. 2009) started at 14.4 ka BP, indicating climatic amelioration.

**The Younger Dryas stadial**

Rasmussen et al. (2014) suggested that the Younger Dryas chronozone can be used as a non-archive-specific synonym for the stadial period between the Bolling – Allerød and the Holocene that lasted approximately between 12.9 and 11.7 ka BP. In the Sihailongwan pollen record, the Younger Dryas cooling event begins at 12 680 a BP but lacks an abrupt termination as gradual changes took place between 11 600 and 12 250 a BP. The Younger Dryas was therefore estimated to have lasted between 1000–1300 years (Stebich et al. 2009). In the Lake Xiaolongwan diatom sequence, the Younger Dryas event corresponds to XLON-4 and XLON-5a and has a duration of c. 1100 years.

The short zone XLON-4 (12 840–12 490 as BP) is marked by a sharp increase in varve thickness, a switch back to the clastic-chrysophyte cyst varve type, a rise in the clastic content and a modest increase in the flux of benthic diatoms. In the diatom assemblage the main feature is the large increase in *S. minutulus* concomitant with the sharp decline in *A. formosa*. The ecology of these two spring-blooming diatoms essentially differs by their nutrient requirements. *S. minutulus* has high P demands and very low Si requirements, which makes it a specialist of conditions with a low silicon to phosphorus ratio (Si:P) (Interlandi et al. 1999; Lynn et al. 2000). By contrast *A. formosa* has relatively high silicon requirements (and also low requirements for growth under phosphorus limitation), which implies that it can often dominate the plankton at high Si:P ratios (Sommier 1983; Van Donk & Kilham 1990). Therefore, the high abundance of *S. minutulus* and the decrease in the percentages of *A. formosa* can be interpreted as a shift towards low Si:P conditions. This shift may be caused by an increased supply of P, a decreased supply of Si or both.

In Lake Xiaolongwan, a drier climate would promote *Stephanodiscus* by lowering the Si:P ratio as the loading of silica to the lake is closely linked to the amount of precipitation in these maar lakes (Schettler et al. 2006). Simultaneously, in the Lake Sihailongwan pollen record a reduction in vegetation density and the re-expansion of *Larix* and *Picea* were interpreted as indicating a colder and drier climate (Stebich et al. 2009). Generally weak monsoon conditions, starting at 12 850 a BP, were also reported from the speleothem record of Kulishu Cave in northern China (Ma et al. 2010).
2012). Park et al. (2014), however, reported from Hannon maar palaeolake in South Korea that conditions remained humid until 12.6 ka BP. Hong et al. (2010) also reported wet conditions during the Younger Dryas from analysing peat cellulose 13C from the Hani peat, located near Lake Xiaolongwan. Hong et al.’s (2010) interpretation is however very controversial and was refuted by Schettler (2011) and Stebich et al. (2011).

Alternatively, the increase in *Stephanodiscus* may have been caused by an increased loading of P not related to a change in precipitation. Interestingly, in the varved sequence of Meerfelder Maar (Germany) Brauer et al. (1999a,b) reported that the start of the Younger Dryas was also characterized by a large increase in varve thickness. Varves in that interval were composed by monospecific spring/summer layers of *Stephanodiscus* and autumn/winter layers enriched in allochthonous minerogenic matter, plant detritus and abundant epiphytic diatoms. They interpreted these changes as a significant eutrophication event caused by soil erosion and reworking of littoral sediments. Soil erosion was caused by the demise of forest vegetation, whereas reworking of littoral sediments was linked to a lowering of the lake level owing to drier conditions. More recently, however, Lane et al. (2013) proposed that the *Stephanodiscus* blooms observed in the Meerfelder Maar sequence were wind-driven. In Lake Suigetsu, in Japan, the onset of the Younger Dryas is characterized by a diatom shift that indicates an intensified winter monsoon bringing stronger winds (more turbulence to the water column) and thicker snow cover (increase surface runoff associated with meltwater in spring) (Kossler et al. 2011). Therefore, the diatom changes observed in Lake Xiaolongwan at c. 12.8 ka BP may have been caused by a combination of windier and/or drier climate that caused an increase in P loading and/or a decline in the supply of Si. In any case it is very unlikely that these diatom shifts were caused by an increase in summer precipitation. Therefore, the Xiaolongwan diatom record does not support the assertions of Hong et al. (2010) for a wet Younger Dryas, at least not from the onset.

The start of XLON-5a (12 490–11 740 a BP) is marked by a peak in varve thickness caused by an increase in clastic content of the sediment. Following this short event both TOC and TN increase. The rise in the C:N ratio (Fig. 5) suggests an increase in the input of organic matter from the catchment. An increase in benthic diatoms (both in terms of percentages and flux) at the top of this zone may indicate some reworking of the littoral sediments. The appearance of varve of the dinocyst-chrysophyte cysts between 12.2 and 12 ka BP also suggests an increased input of allochthonous organic matter and may match with one of the centennial warming/wetting fluctuations observed in several Chinese speleothem records (Ma et al. 2012; Liu et al. 2013) and in other Eurasian records such as Meerfelder Maar (Rach et al. 2014). Simultaneously in the diatom assemblages, *S. minutulus* declines whereas *D. tatraica* and to a lesser extent *A. formosa* increase. As seen earlier, *D. tatraica* would be favoured by less transparent water (higher DOC content) and a shallower mixing depth (less windy conditions).

From the above it seems that the Younger Dryas in Xiaolongwan has two distinct phases (XLON-4 and XLON-5a). A similar bipartite structure has been observed in several European lake records (Neugebauer et al. 2012; Lane et al. 2013). Basing their studies on several very well-dated northern European sediment records, Lane et al. (2013) and Muschitiello & Wohlfarth (2015) showed that the onset of the Younger Dryas was asynchronous at the continental scale. Considering the limitation of our age model and the time resolution of our record, we refrain from evaluating how the timing of the Younger Dryas at Lake Xiaolongwan compares with these records.

The early Holocene

In the Lake Sihailongwan pollen record the start of the Holocene is characterized by an increase in *Betula* and increasing forest cover density occurring at 11 650 a BP (Stebich et al. 2009). For Lake Xiaolongwan, the zone XLON-5b (11 740–11 350 a BP) is marked by a return to high percentages of the spring-blooming *S. minutulus*. There are no large changes in varve type, varve thickness or geochemical proxies associated with this diatom shift. This suggests that this was caused by a direct effect of climate on the seasonal diatom succession (earlier and longer springs as seen earlier) rather than a catchment-mediated change in nutrient and/or light conditions as seen for the start of the Younger Dryas.

The following zone, XLON-5c (11 350–11 170 a BP), is characterized by abrupt rises in TOC and TN and a change of varve type from chrysophyte cysts to ‘chrysophyte cysts-dinocysts’. In the diatom assemblages, the collapse in *S. minutulus* numbers is associated with a rise in *A. formosa* and then *D. tatraica*. As seen above, the increase in *D. tatraica* was maybe caused by increasingly coloured waters. It is approximately at that time that carbon started to accumulate in peatlands of the LGVF, such as the Hani peat located nearby Lake Xiaolongwan (Xing et al. 2015). Long time series data sets have shown that light availability is the main factor governing *A. formosa*’s rate of cell increase in spring. The greater rates of increase are caused by a late start of the growth period (owing to a late date of ice-cover break-up) and hence growth under higher light conditions (Maberly et al. 1994). It is noticeable that during this time interval late spring (June) insolation was at its maximum (Fig. 5). This taxon, unlike *S. minutulus*, would therefore benefit
from a longer period of ice cover and high light conditions in late spring. This short zone, marked by the end of *S. minutulus*’ dominance, may correspond with the 11.4 ka BP cold event reported in the Greenland ice-core records (Rasmussen et al. 2014). It is also called the Pre-Boreal oscillation and was reported in South Korea (Park et al. 2014) but not in the pollen record from Lake Si hailongwan (Stebich et al. 2009).

In XLO N-6 (11 170–10 690 a BP), an increase in the C:N ratio (Fig. 5) indicates further input of organic matter from the catchment. The diatom assemblages are largely dominated by benthic diatoms as the BVAR of planktonic diatoms collapses. Simultaneously, there is a change of varve type from chrysophyte cyst-dinocyst to dinocyst. Therefore, planktonic diatoms would appear to have been out-competed by Dinophyceae. This shift to dominance of Dinophyceae may have been caused by increased dissolved organic matter of terrestrial origin in the lake water (Purina et al. 2004; Chu et al. 2008). At Si hailongwan this time interval is marked by a sharp increase in dust accumulation that indicates a shift towards drier conditions in northern China (Zhu et al. 2013). Reduced snow cover under drier conditions may have also been a factor in shifting the phytoplankton composition as Weyhenmeyer et al. (1999) showed that Dinophyceae are favoured over diatoms when the spring phytoplankton peak occurs below the ice cover, i.e. before ice break-up, when light conditions are sufficient (i.e. if the ice is clear, without thick snow cover). Allelopathic substances released by Dinophyceae have also been observed to inhibit nutrient acquisition by centric diatoms, especially those of small size (Lyczkowski & Karp-Boss 2014). These effects may have contributed to reducing the growth of planktonic diatoms once Dinophyceae started to dominate.

Conclusions
The diatom and geochemical data presented here for the Xiaolongwan Lateglacial and early Holocene sedimentary sequence provide a detailed record of environmental and climatic change during the last deglaciation. Lake Xiaolongwan appears to have recorded some shifts of lower amplitude that were not reported in the pollen results from the neighbouring Lake Si hailongwan (Stebich et al. 2009). In particular, the two diatom assemblage zones that characterize the Younger Dryas suggest a bipartite division of this stadial event as already reported in some studies from eastern Asia (Park et al. 2014) and Europe (Lane et al. 2013). Interestingly, subdivision of the Younger Dryas is a common feature in the diatom records from Europe as reviewed by Buczkó et al. (2012). There is also a short event at c. 11 350 a BP that most likely matches with the Pre-Boreal oscillation. The quasi-synchronicity of these events with the oscillations described in the North Atlantic realm demonstrates a strong control of the climate in northeastern China by North Atlantic dynamics at centennial and millennial time scales.

This sequence is also useful as it illustrates the complexity of interpreting shifts in diatom assemblages as these may be caused by either the direct effects of seasonal climate on the limnology of the lake (in particular on the duration and timing of ice cover, and length and strength of spring mixing) and/or catchment-mediated effects on the concentrations of nutrients (P and Si) and on the light conditions (via input of dissolved organic matter). This is most obvious with the shifts in abundance of *S. minutulus*. Unlike in other studies (e.g. Bradbury 1988; Rioual et al. 2007), in which increases of the spring-blooming *S. minutulus* were unequivocally associated with warmer conditions (shorter ice cover), in the Lateglacial sequence of Lake Xiaolongwan this species is also associated with the start of a cold event, as in that case its growth was stimulated by windier, drier conditions as well as increased input of nutrients from the catchment and/or the littoral zone of the lake.

This sequence also highlights the importance of considering biotic interactions (e.g. competition, allelopathy) between the various groups of phytoplanktonic algae (diatoms, chrysophytes and Dinophyceae in the case of Lake Xiaolongwan) when interpreting the shifts in assemblages observed in the fossil record.

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References


Procházková, L., Houk, V. & Nedbalová, L. 2012: *Discostella tatrica* sp. nov. (Bacillariophyceae) - a small centric diatom from the Tatra Mountain lakes (Slovakia/Poland). *Fottea* 12, 1–12.


Solak, C. N. & Kulikovskiy, M. 2013: Species composition and distribution of centric diatoms from Türkmen Mountain (Sakarya River Basin/Turkey). Turkish Journal of Botany 37, 589–596.


Stebich, M., Mingram, J., Han, J. & Liu, J. 2009: Late Pleistocene spread of (cool-) temperate forests in Northeast China and climate changes synchronous with the North Atlantic region. Global and Planetary Change 65, 56–70.


Supporting Information

Additional Supporting Information may be found in the online version of this article at http://www.boreas.dk.