Neoglacial trends in diatom dynamics from a small alpine lake in the Qinling mountains of central China

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Abstract. During the latter stages of the Holocene, and prior to anthropogenic global warming, the Earth underwent a period of cooling called the neoglacial. The neoglacial is associated with declining summer insolation and changes to Earth’s surface albedo. Although impacts varied globally, in China the neoglacial was generally associated with a cooler climate and an attenuated Asian summer monsoon. Few studies in central China, however, have explored the impact of neoglacial cooling on freshwater diversity, especially in alpine regions. Here we take a palaeolimnological approach to characterise multi-decadal variability in diatom community composition, ecological guilds, and compositional turnover over the past 3500 years from the alpine Yuhuang Chi lake on Mount Taibai in the Qinling mountains. Diatoms in the high-profile guild dominate much of the record from 3500 to 615 cal BP, which suggests that few nutrients in the lake were limiting overall, and disturbance and herbivory were likely low. After 615 cal BP, low-profile and planktic guild diatoms increase, suggesting greater turbulence in the lake, alongside a decline in available nutrients. Diatom turnover highlights periods in the lake history when deterministic processes structured diatom communities. For example, an abrupt decline in turnover is coincident with the shift from high- to low-profile diatoms at 615 cal BP, and this is likely due to the onset of the Little Ice Age in the region. We suggest that Yuhuang Chi lake became more shallow during peak regional aridity, which led to the short-lived community restructuring observed in the record.

1 Introduction

Alpine ecosystems are some of the most sensitive to changing climate, due in part to elevation-dependent warming, i.e. the amplification of warming at higher altitudes (Yan and Liu, 2014; Pepin et al., 2015). Understanding how high-altitude ecosystems respond to changing climate is a matter of urgency, because not only do these regions act as “water towers” supplying water to huge populations downstream (Messerli et al., 2004; Buytaert et al., 2017) but they also provide habitats to many iconic species that are classified by the IUCN (International Union for Conservation of Nature) as being vulnerable (Fan et al., 2014). Alpine freshwaters have multiple ecosystem functions (Messerli et al., 2004; Buytaert et al., 2017) and provide many ecosystem services such as freshwater regulation and habitat provision (Grêt-Regamey et al., 2012). Their multifunctionality depends on local species communities and how species vary through space and time (beta diversity) and are driven by ecosystem properties, environmental gradients, and species interactions (Korhonen et al., 2010).

Beta diversity links biodiversity at regional and local scales, and it may take the form of non-directional variation or directional turnover (Anderson et al., 2011). Long-term records of beta diversity commonly focus on the amount of compositional turnover over time, which provides important information on ecosystem functioning (Birks, 2007). For example, estimating species turnover assumes that species are
lost and gained over time in response to resource availabil-
ity, competition, historical events, and environmental fac-
tors (Korhonen et al., 2010) over both recent (Smol et al.,
2005) and long timescales (Leprieur et al., 2011). How-
ever, because the concept of beta diversity has so many
meanings to different disciplines, we take the approach of
Felde et al. (2020) and just focus on directional composi-
tional turnover, which is appropriate for palaeolimnological
datasets from a single lake.

Natural archives are an important resource for reconstruc-
ting past environments where long-term historical and/or
instrumental records are either scarce or absent. In cen-
tral China, speleothems provide exceptional, high-resolution
records of monsoon intensity, allowing for periods of mul-
tiannual and multi-decadal drought to be determined (Wang
et al., 2005). Yet there are relatively few studies (Liu et al.,
2017) which have explored multi-decadal records of biodi-
versity change over similar timescales, leaving a fundamen-
tal gap in understanding as to how biodiversity in freshwater
ecosystems, especially at higher altitudes, responds to pe-
riods of climate variability. Reconstructing the impacts of
past climate on freshwater ecosystems is fundamental to un-
derstanding how freshwater biodiversity may respond to fu-
ture climate, especially during periods of rapid change. Here
we focus on the neoglacial, which spans at least the past
cia. 3500 years.

The neoglacial, characterised by increasingly cooler tem-
peratures, follows on from globally warmer temperatures
of the early to mid-Holocene. The extent of cooling var-
ied regionally, being most pronounced in the extratropical
Northern Hemisphere (Marcott et al., 2013). The most im-
portant driver of Northern Hemisphere cooling was declin-
ing summer insolation (Marcott et al., 2013) in conjunc-
tion with changes in albedo on the Earth’s surface, which
was linked to feedbacks from vegetation and snow/ice. In
China, the neoglacial resulted in the persistent decline in
monsoon intensity in southern China (Wang et al., 2005) and
a rapid decline in precipitation in northern China (F. Chen
et al., 2015), leading to increased aridity and major shifts
in vegetation communities (Zhou et al., 2010). Superim-
posed on the insolation-driven neoglacial were notable pe-
riods of sub-Milankovitch centennial-scale climatic events
(e.g. Mayewski et al., 2004; Mann et al., 2009; Wanner et
al., 2014), including the 2800 BP event (Hall et al., 2004),
the Medieval Climatic Anomaly (MCA) (ca. 1000–1300 CE)
and the Little Ice Age (LIA) (ca. 1300–1850 CE). The latter
two events are well expressed throughout China; medieval
temperatures were generally warmer than the following cen-
turies spanning the LIA (Cook et al., 2013; J. Chen et al.,
2015). However, while the LIA generally resulted in periods
of aridity (e.g. Wang et al., 2005; Tan et al., 2011; F. Chen
et al., 2015), in-depth research highlights a more heterogenous
response across China (e.g. Cook et al., 2010), with some
central and southern regions becoming wetter due to inter-
plays between the westerly jet stream and the Asian summer
monsoon (ASM) (Tan et al., 2018).

Freshwater ecosystems in the Qinling mountains of cen-
tral China provide natural capital and ecosystem services for
local and regional populations, and understanding the impact
of monsoon variability on ecosystem functioning has the po-
tential to add insight into how freshwater biodiversity may
respond to future climate change and predicted increases in
mean annual precipitation (Guo et al., 2017). In this study,
we reconstruct neoglacial trends in diatom community com-
position, their ecological guilds, and compositional turnover
at a multi-decadal resolution over the past 3500 years.

Study region
The Qinling mountains are widely recognised for their con-
servation importance and as a biodiversity hotspot; they are a
refuge for many Tertiary plants (Zhang et al., 2017) and vul-
nerable species such as the Giant Panda (Fan et al., 2014).
The region is climatically very sensitive, as it separates the
northern subtropical zone of China from the country’s central
warm-temperate zone (Fig. 1). Mount Taibai (34°N, 108°E;
3767 m) is the highest mountain in the range, with a timber-
line at ca. 3370 m and treeline at ca. 3600 m (Liu et al., 2002).
The mountain is classified as a glacial heritage site, because
Quaternary glaciations are well preserved, especially the last
 glaciation (Yang et al., 2018). On Mount Taibai there are sev-
eral clusters of cirque lakes, and our study site, Yuhuang Chi
(YHC) lake, is found in one of these clusters. It is a cirque
and moraine lake at 3370 m a.s.l., placing it in the Larix for-
est – subalpine meadow ecotone. Specifically, Larix chinensis
Beissn grows in podzolic soils between 2000 and 3500 m, and
it is associated with a cold, arid climate. Regional an-
nual average temperature is below 8 °C and annual precipi-
tation is ca. 840–960 mm. Yuhuang Chi lake has a maximum
depth of 21.5 m and an area of ca. 23 600 m². No shoreline
macrophytes were observed during coring, but it was winter
when the lake was frozen. Using a YSI ProDSS multiparam-
eter water quality meter, surface water pH was measured at
6.84 pH units.

2 Methods
2.1 Coring, age model, and total organic carbon
A 135 cm sediment core (YHC15A) was collected in
2015 CE using a 6 cm diameter piston corer from the cen-
tral region of Yuhuang Chi lake. The highly humified lake
sediments contained no sizable macrofossils for radiocar-
bon analyses. Radiocarbon dating was instead carried out on
five bulk organic sediment samples using accelerator mass
spectrometry (AMS) at Beta Analytic, USA. There is a ra-
diocarbon reservoir effect evident in the data (likely from
old soil carbon input from the catchment), so we used a
quadratic extrapolation to determine reservoir ages (Hou
et al., 2012). All the radiocarbon dates were fitted with a quadratic function ($^{14}\text{C}_{\text{age}} = 0.0693 \text{depth}^2 + 17.31 \text{depth} + 1340; R^2 = 0.9994$), so we determined the top (0 cm) with a 1340-year reservoir age effect. An age–depth model was developed with smooth fit using CLAM 2.2 (Blaauw, 2010) in R, using the Intcal13 (Reimer et al., 2013) calibration curve. Total organic carbon (TOC) provides an estimate of the amount of organic carbon that escapes remineralisation before being incorporated into lake sediments. TOC was measured on contiguous 1 cm samples using an elemental analyser (Flash EA 1112).

2.2 Diatoms

Diatom analysis was performed on alternate 1 cm thick sediment samples. Approximately 0.1 g of wet sediment from each sample was prepared using standard procedures outlined in Battarbee et al. (2001). Organic matter was removed by heating each sample in 30% H$_2$O$_2$ before 10% HCl was added to remove carbonates and any excess H$_2$O$_2$. Diatom concentrations were calculated through the addition of divinylbenzene (DVB) microspheres (concentration $8.02 \times 10^5$ spheres cm$^{-3}$) to diatom suspensions, and diatom fluxes were calculated using sediment accumulation rates. Diatom suspensions were diluted and then pipetted onto coverslips to dry before being fixed onto microscope slides with Naphrax®. Using a Zeiss Axiostar Plus® light microscope, diatoms were counted at 1000× magnification under an oil-immersion objective and phase contrast. A minimum of 300 diatom valves (min 331, max 591) were counted for each of the 67 samples. Diatoms were identified using a variety of flora including Krammer and Lange-Bertalot (1986, 1988, 1991a, b), Williams and Round (1987), and Lange-Bertalot (2001).

Diatom species were categorised according to ecological guilds commonly associated with the abundance of available resources (e.g. light, nutrients) and disturbance (e.g. grazing and turbulence) (after Passy, 2007; Rimet and Bouchez, 2012). The low-profile guild includes diatoms which attach themselves to substrates in erect, prostrate, and adnate forms, are very slow moving (Passy, 2007), and are generally adapted to low nutrient levels. High-profile guild diatoms are those of tall stature (e.g. they are filamentous, chain-forming, or found in mucilage tubes), and they are generally adapted to high levels of nutrients and low levels of disturbance (Passy, 2007). Motile diatoms are relatively fast-moving species that are tolerant of high levels of nutrients (Passy, 2007) and silting processes (Battegazzore et al., 2004). A new planktic guild was determined by Rimet and Bouchez (2012), which includes centric species able to resist sedimentation in lake ecosystems.

2.3 Multivariate analyses

The magnitude of diatom turnover was initially estimated using detrended correspondence analysis (DCA), with square root transformation of the species data to stabilise variance and rare species being weighted lower. The axis 1 gradient length was 1.44 standard deviation units, so diatom abundances were reanalysed using principal components analysis (PCA). A log–linear contrast PCA was undertaken (appropriate for closed, relative abundance data; Lotter and Birks, 1993), with symmetric scaling of ordination scores so that scaling of both samples and species were optimised. Species compositional turnover was estimated using detrended canonical correspondence analysis (DCCA), with the diatom data constrained using dates from the calibrated age model (Smol et al., 2005). We used DCCA to estimate compositional turnover because sample scores are
3 Results

3.1 Core description and age model

The lithology of the 135 cm long YHC15A core consisted entirely of grey-brown highly humified gyttja. Radiocarbon dates of TOC are given in Table 1, and an age–depth model determined using CLAM 2.2 (Blaauw, 2010) (shown in Fig. 2). Sediment rates are lower during the early part of the record, before ca. 1400 cal BP (0.28 mm yr\(^{-1}\)), compared to sediments deposited during the past 1400 years (0.48 mm yr\(^{-1}\)).

3.2 Diatoms

A total of 170 species of diatom were identified from Yuhuang Chi lake, with the majority (120 species) being only of low occurrence (< 1 % in one or more samples). For much of the stratigraphy, diatoms were dominated by fragilarioids and naviculoids up to ca. 930 cal BP, (1020 CE) after which they decline to be replaced by Monoraphid- and Gomphonema-type taxa alongside the centric Lindavia. Stratigraphically constrained cluster analysis by incremental sum of squares analysis (CONISS) on diatom-relative abundance data reveals three zones: zone 1 (ca. 3550–2300 cal BP), zone 2 (ca. 2300–615 cal BP), and zone 3 (ca. 615 cal BP–present) (Figs. 3, 4). Zone 1 is dominated by diatoms in the high-profile guild (Fig. 4), notably fragilarioids Staurororma exiguisformis and Stauroriirella pinnata. Diatoms in the motile guild are well represented by the naviculoid Humidophila schmassmannii, together with Diadesmis gallica, Mayamaea atomus, and Mayamaea fossalis. The decline in S. exiguisformis at the top of the zone is accompanied by an increase in Pseudostaurosira brevistriata and a decline in motile diatoms, e.g. M. atomus. In zone 1, there is a gradual decline in compositional turnover and PCA1 sample scores. Zone 2 is marked by a notable increase in the planktic Lindavia bodanica and increasing P. brevistriata and Pseudo-staurosorosa pseudoconstruaea. Diversity in zone 2 exhibits a rather stable flora, dominated by P. brevistriata, P. pseudoconstruaea, and L. bodanica, while Gomphonema ovaceoides and Karayaevia suchlandtii appear in the record for the first time at ca. 1400 and 1070 cal BP, respectively. Motile diatoms become persistently lower than the mean at this time during zone 2, while low-profile diatom abundances increase to fluctuate about the average (Fig. 4). Zone 3 occurs just before a major change in diatom turnover (Fig. 3). Several species decline from the record altogether including S. exiguisformis and H. schmassmannii, while other species reach peak abundance for the whole profile, including L. bodanica, G. ovaceoides, and diatoms which occupy the low-profile guild status in general (Fig. 4). Denticula subtilis appears in the record for the first time at ca. 400 cal BP (1550 CE). During zone 3, low-profile and planktic diatoms increase to their highest values for the whole record, while high-profile and motile diatoms are persistently lower than the mean. Diatom fluxes range from 0.07 × 10\(^6\) to 7.02 × 10\(^6\) valves cm\(^{-2}\) yr\(^{-1}\) (mean of 1.85 × 10\(^6\) valves cm\(^{-2}\) yr\(^{-1}\)). When centred around the mean, fluxes are highest in zone 2, between ca. 1500 and 800 cal BP (450–1150 CE), but decline at ca. 800 cal BP (1150 CE) to lowest values from ca. 600 cal BP (1350 CE) to the present (Fig. 3). The % TOC values are low and range from 2.6%–4.3% (mean 3.45%). TOC values were highest in zone 1, declined in zone 2, and reached lowest values, coincident with lowest values for compositional turnover, at ca. 1645 CE.

PCA highlights a very strong first axis gradient which accounts for over 45 % of variation in the diatom data.
Table 1. AMS-14C radiocarbon dates from Yuhuang Chi lake (core YHC15A).

| Lab no.  | Depth (cm) | Material      | δ13C (‰ VPDB) | 14C date ± error (BP) | 14C date minus 1340 reservoir age (BP) | Weighted calibrated age (no error) (cal BP) |
|----------|------------|---------------|----------------|-----------------------|----------------------------------------|------------------------------------------|
| Beta-425231 | 10         | Bulk organic  | −24.6          | 1530 ± 30             | 190 ± 30                               | 168                                      |
| Beta-425232 | 30         | Bulk organic  | −24.7          | 1920 ± 30             | 580 ± 30                               | 595                                      |
| Beta-425233 | 50         | Bulk organic  | −24.9          | 2370 ± 30             | 1030 ± 30                              | 949                                      |
| Beta-417757 | 70         | Bulk organic  | −24.8          | 2870 ± 30             | 1530 ± 30                              | 1423                                     |
| Beta-425234 | 110        | Bulk organic  | −24.8          | 4140 ± 30             | 2800 ± 30                              | 2868                                     |
| Beta-417758 | 130        | Bulk organic  | −24.9          | 4730 ± 30             | 3390 ± 30                              | 3584                                     |

Figure 3. Diatoms shown greater than 3% in more than one sample. Diatom species are given as relative abundances. Also shown are PCA axis-1 scores for species and genera, compositional turnover values, planktonic-to-benthic (P/B) ratio data, and mean-centred diatom fluxes. Zones were delimited using CONISS – see text for details.

Trends in PCA-1 are most clearly seen in Fig. 5, as deviations around the mean. Breakpoint analysis indicates a major (p < 0.001) change in PCA axis 1 scores (Table 2), close to the transition when PCA values switch from being higher than the mean to being lower than the mean, and low values persist for the rest of the record. Diatom compositional turnover (estimated from DCCA; 1.033 SD units) shows a similar pattern to PCA-1, with breakpoints identified at ca. 515 cal BP ± 40 years (ca. 1435 CE) and 335 cal BP ± 33 years (ca. 1615 CE) (Table 2; Fig. 5).

4 Discussion

4.1 Diatom assemblage change

Sedimentary diatom assemblages in Yuhuang Chi lake are dominated by species in the Fragilariaceae (Fig. 3) from 3500 to 615 cal BP. Fragilarioids are often opportunistic, dominating assemblages in alpine and arctic lakes with a short growing season and long periods of ice cover (Lotter and Bigler, 2000). For example, July air temperature and ice cover duration have both been shown to have a significant influence on the abundance of fragilarioids in the European Alps (Schmidt et al., 2004), while in a subalpine lake in the Eastern Sayan Mountains (Russia), insolation and Northern Hemisphere air temperatures played a strong role on modulating fragilarioid responses through the Holocene (Mackay et al., 2012). The early part of our record is dominated by Stauroforma exiguisformis, a species common in dystrophic lakes (Flower et al., 1996). Its high abundance may be related to relatively high carbon sequestration during the very early part of the record in zone 1 (Fig. 5c). The decline in S. exiguisformis is concomitant with the increase in Humidophila schmassmannii and may be indicative of Yuhuang Chi lake becoming less dystrophic (Buczko et al., 2015), which is perhaps linked to a progressively cooler (Stebich et al., 2015) and more arid (F. Chen et al., 2015) climate (Fig. 6). The decline in H. schmassmannii after ca. 2800 cal BP further tracks the switch to a progressively cooler and more arid climate (Wang et al., 2005; J. Chen et al., 2015).

Growth of the planktic diatom L. bodanica in oligotrophic lakes is related to increased mixing depth (Saros and Anderson, 2015), because it can tolerate relatively low light
Figure 4. All diatoms were classified into one of four guilds (after Passy, 2007, and Rimet and Bouchez, 2012): low profile (guild 1), high profile (guild 2), motile (guild 3), and planktic (guild 4). Guilds are presented as relative abundances (%) to the left and deviations around the mean to the right.

Table 2. Significant breakpoints in diatom trend data ($p < 0.001$).

|                       | Breakpoint 1  | $p$ value | Breakpoint 2  | $p$ value |
|-----------------------|--------------|-----------|--------------|-----------|
| Species PCA           | 1850 ± 200   | $p < 0.001$ | none         |           |
| Compositional turnover| 515 ± 97     | $p < 0.001$ | 335 BP ± 33  | $p < 0.001$ |
| Guild 2 – high profile| 2910 ± 127   | $p < 0.001$ | 1565 BP ± 175| $p < 0.001$ |
| Guild 3 – motile      | 2880 ± 69    | $p < 0.001$ | 1960 BP ± 128| $p < 0.001$ |

levels and take advantage of increased nutrient availability (Malik and Saros, 2016). Therefore, as the neoglacial progressed, mixing of the lake may have increased gradually, allowing this taxon to eventually dominate for most of the past 615 years, even though diatom fluxes (Fig. 3) and % TOC (Fig. 5) were relatively low, which is indicative of overall low diatom productivity.

4.2 Diatom traits

Even though we do not have quantitative estimates of nutrients in this remote lake, we can start to make inferences about nutrient availability from the traits exhibited by the diatom communities themselves. For example, frustularioids identified at Yuhuang Chi lake can be classified as high-profile diatoms (i.e. of tall stature), i.e. able to compete effectively for resources such as nutrients and light. However, their tall stature also makes them susceptible to disturbance (Passy, 2007), including turbulence in alpine lakes with short water-residency times (Rimet et al., 2019). Their dominance at Yuhuang Chi lake from 3500 to 615 cal BP suggests that nutrients and light were not limiting (Passy and Larson, 2019) for much of the sequence. Herbivory was likely low as well (Passy and Larson, 2019), because high-profile diatoms are not well adapted to high grazing pressures, which are generally low in alpine lakes (Rimet et al., 2019).

The decline in high-profile guild values with a concomitant increase in low-profile and planktic guilds since 615 cal BP suggests that environmental conditions in Yuhuang Chi lake changed. Diatoms belonging to the low-profile guild attach themselves to substrates in erect, prostrate, and adnate forms (Passy, 2007), which means that although they are able to tolerate relatively high disturbance, they also need to withstand an increase in the number of resources that becomes limiting to them; i.e. they are well adapted to low nutrient concentrations (Berthon et al., 2011). The planktic guild was proposed by Rimet and Bouchez (2012) alongside the high, low, and motile guilds determined by Passy (2007), as diatoms are able to resist sedimentation through the water column and, in our lake, this guild is dominated by *L. bodanica*. The fact that *L. bodanica*
can tolerate low light conditions, and through turbulence of the water column obtain the nutrients that it needs to grow, is again indicative of resources, such as nutrients, becoming more limiting since the middle of the 14th century.

4.3 Diatom compositional turnover

In aquatic environments, when disturbance increases or the number of limiting resources increases, such as a decline in nutrient and/or light availability, deterministic processes become more important than stochastic ones in structuring aquatic communities (Chase, 2010). Increasing deterministic processes leads to a decline in compositional turnover because disturbance or stress can act as environmental filters (Larson et al., 2016) through niche selection. The decline in turnover between 3100 and 1900 cal BP is gradual, and it reflects the slow long-term change in low-profile guild diatoms increasing and motile guild diatoms declining. An increase in low-profile diatoms hints at increasing disturbance and/or declining nutrients (Passy, 2007), while a decline in motile diatoms may be indicative of a decline in silation processes within the lake (Battegazzore et al., 2004). Over this time period our data also show a marked decline in TOC sequestration to the bottom sediments (Fig. 5c). We suggest therefore that the diatom and TOC data both point to a reduction in dissolved organic carbon in Yuhuang Chi lake concurrent with cooling regional temperatures and increased aridity (F. Chen et al., 2015).

There are also periods when compositional turnover stabilised or even increased slightly during the neoglacial, e.g. between ca. 1900 and 1400 cal BP (Fig. 6a). This period coincides with distinctly warmer Arctic and European temperatures (PAGES 2k Consortium, 2013), commonly referred to as the “Roman Warm Period”. Precipitation in central China is closely tied to the intensity of the Asian summer monsoon (ASM) (F. Chen et al., 2015), and at this time the summer monsoon was rather stable (Fig. 6d). Diatoms were dominated by high-profile species, indicating that nutrients were not in limited supply, perhaps being washed in from the catchment with summer monsoon rains.

Between 1400 and 615 cal BP (550–1335 CE), turnover, although lower than average (Fig. 6a), did not decline (Fig. 3), indicating an increased competition between species (Larson et al., 2016). This period coincides with the Medieval Climatic Anomaly (MCA), sometimes referred to as the Medieval Warm Period. Sub-decadal isotopic records from a stalagmite from a Buddha cave in the Qinling mountains indicate a period of a warm, wet climate between ca. 985 and 475 cal BP (965–1475 CE) (Paulsen et al., 2003), while paleological records, including the beginning of tree flowering along the Yellow and Yangtze rivers, show that winter half-year temperatures were high between 1380–640 cal BP (570–1310 CE) (Ge et al., 2003). An increased presence of Quercus and Betula pollen on Mount Taibai also suggest warm, wet conditions (Li et al., 2005; Wang et al., 2016) with temperatures perhaps being as much as 2°C warmer than mean annual temperatures observed today (Li et al., 2005). These local climate indicators tie in well with regional monsoon patterns; monsoon strength was higher in central (Paulsen et al., 2003; J. Chen et al., 2015; Wang et al., 2016) and northeast China (F. Chen et al., 2015; J. Chen et al., 2015) than north-west China (J. Chen et al., 2015), while, globally, low-latitude temperatures increased (Fig. 6d).

4.4 Abrupt ecological change during centennial-scale cold events

Against a backdrop of low Northern Hemisphere summer insolation (Fig. 6g), amplified by centennial-scale oceanic variability (Renssen et al., 2006), late Holocene cold events were caused by several “overlapping” factors (such as volcanic eruptions and solar minima) (Wanner et al., 2014). The most recent wide-scale cold event is the period commonly known as the Little Ice Age approximately 1300–1850 CE, caused by several interacting time-transgressive forcings, including reduced solar activity during the late 17th century (Shindell et al., 2001), increased volcanic activity during the early 19th century (Brönnimann et al., 2019), and overall reduced Gulf Stream flow (Lund et al., 2006). It is the cooling event that we focus on in this study, because cluster analyses of diatom assemblages delineate the boundary between zones 2 and 3 at 615 cal BP (1335 CE), and there are two significant breakpoints in compositional turnover including when turnover is at its lowest in the whole record at ca. 335–330 cal BP (1615–1620 CE) (Table 2).

Describing the Little Ice Age as a period characterised by cooler climate and glacier readvance is rather simplis-
tic, but one that has proven quite resilient, even as its complexities are better understood (e.g. Matthews and Briffa, 2005). As more regions are investigated, impacts extend to changes in aridity as well as temperature. For example, J. Chen et al. (2015) demonstrated that, by and large, regions north of 34° latitude (where our study site is located) were generally drier than regions further south, with the extent of aridity being affected by ocean–atmosphere interactions, such as ENSO (El Niño–Southern Oscillation) and its teleconnections to SE Asia. The LIA is especially characterised by a strengthened Siberian High (SH), a semi-permanent anticyclone centred over Eurasia which strengthens intensively every winter. A strong Siberian High results in a strong East Asian winter monsoon (EAWM) (Zhang et al., 1997). K⁺ concentrations in the GISP (Greenland Ice Sheet Project) ice core clearly show that the Siberian High was especially strong between ca. 550 and 150 calBP (1615–1800 CE) (Fig. 6f), assuming that potassium is likely sourced from central Asian dust via long-range transport to the Greenland ice sheet (Meeker and Mayewski, 2002). Concurrent with increased aridity, global low-latitude temperature records show rapid cooling at this time (Fig. 6b; Marcott et al., 2013), which in China led to very low winter anomalies (Ge et al., 2003) and lowest summer pollen-inferred temperatures in NE China (Fig. 6c).

Very low diatom fluxes characterise the past 800 years at Yuhuang Chi lake (Fig. 3), which is indicative of reduced diatom productivity that is coincident with a prevailing colder climate. Lowest compositional turnover at ca. 335–330 calBP (1615–1620 CE), linked to the disappearance of *S. exiguiformis*, may be due to enhanced frozen soils, leading to reduced carbon transport to the lake, while the disappearance of *H. schmassmannii* may be because it cannot tolerate such low water temperatures (Buczkó et al., 2015), alongside other factors such as a decline in siltation (Battegazzore et al., 2004). *Denticula subtilis* is a very motile diatom, and in the Canadian high Arctic it is characteristic of shallow lakes with elevated conductivity (Antoniades et al., 2005). It may therefore be reflective of the lake becoming more shallow due to increased aridity. Elsewhere, precipitation minima were reconstructed from nearby by Gonghai Lake (F. Chen et al., 2015a) and at the neighbouring Sanqing Chi lake; high *Larix* and *Ephedra* pollen frequencies are interpreted as being indicative of cold, dry conditions (Wang et al., 2016). The fact that minimum turnover and highest values for low-profile diatoms are observed at this time indicates nutrient limitation and/or significant disturbance, which has led to specialised diatoms to occupy niches where competition was very low (Larson et al., 2016). Following harshest conditions for diatom growth in Yuhuang Chi lake during the early 17th cen-
tury, turnover increases once more, which is indicative of increased competition among species (Larson et al., 2016).

While a cold and arid climate during the LIA had a major impact on diatom diversity in Yuhuang Chi lake, impacts from previous centennial-scale cold events, such as the 2800 BP event, are less conclusive. Like the LIA, the event dated at ca. 2800 BP is concurrent with a deep, abrupt reduction in solar activity (Fig. 6f), which led to a decline in surface water temperatures in the North Atlantic (Andersson et al., 2003), weaker meridional overturning circulation (Hall et al., 2004), and sea-ice expansion (Renssen et al., 2006). But although these events led to a rapid weakening in ASM intensity in southern China (Wang et al., 2005), reconstructed precipitation from Gonghai Lake in northern China suggests that aridity was already increasing from ca. 3100 cal BP (Fig. 6d) (J. Chen et al., 2015). There is a small increase in GISP2 K+ concentrations, which suggests that the Siberian High during the time of the 2800 BP event did not reach the strengths observed during the LIA (Fig. 6e), but still led to regional summertime cooling (Fig. 6c, Stebich et al., 2015). At Yuhuang Chi lake, these changes in climate may have caused the small, temporary decline in both compositional turnover and total diatom flux but also a significant decline in high-profile diatoms that is concomitant with an increase in L. bodanica. This may suggest increased water column instability and turbulence in the lake (Saros and Anderson, 2015).

5 Conclusions

Diatom turnover in the Qinling mountains of central China demonstrates strong directional change. The decline in turnover over the past 3500 years mirrors declining low-latitude June insolation, which drives overall low-latitude cooling (Marcott et al., 2013). This suggests a strong link between orbitally forced climate change and increasingly deterministic processes affecting aquatic ecosystems in this high-altitude region of central China. Over the last 1300 years, impacts related to the Medieval Climatic Anomaly and the Little Ice Age are also expressed in the palaeolimnological records from Yuhuang Chi lake. Increased diatom fluxes (Fig. 3) are coincident with increased regional summer precipitation during the MCA (F. Chen et al., 2015). Colder, more arid conditions during the Little Ice Age, linked to a very strong Siberian High, led to lowest diatom turnover and carbon sequestration for the past 3500 years, possibly due to the lake becoming more shallow at this time. Our study highlights the value of interpreting diatom changes through compositional turnover and ecological trait analyses of their growth forms.

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