A chironomid-based record of temperature variability during the past 4000 years in northern China and its possible societal implications

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Abstract: Long-term, high-resolution temperature records which combine an unambiguous proxy and precise dating are rare in China. In addition, the societal implications of past temperature change on a regional scale have not been sufficiently assessed. Here, based on the modern relationship between chironomids and temperature, we use fossil chironomid assemblages in a precisely-dated sediment core from Gonghai Lake to explore temperature variability during the past 4000 years in northern China. Subsequently, we address the possible regional societal implications of temperature change through a statistical analysis of the occurrence of wars. Our results show that: (1) the mean annual temperature (TANN) was relatively high from 4000-2700 cal yr BP, decreased gradually from 2700-1270 cal yr BP, and then fluctuated during the last 1270 years. (2) A cold climatic event in the Era of Disunity, the Sui-Tang Warm Period (STWP), the Medieval Warm Period (MWP) and the Little Ice Age (LIA) can all be recognized in the paleotemperature record, as well as in many other temperature reconstructions in China. This suggests that our chironomid-inferred temperature record for the Gonghai Lake region is representative. (3) Local wars in Shanxi Province, documented in the historical literature during the past 2700 years, are statistically significantly correlated with changes in temperature, and the relationship is a good example of the potential societal implications of temperature change on a regional scale.

Keywords: chironomids, temperature change, northern China, late-Holocene, societal implications

1 Introduction

Climate change presents new and significant challenges for human society, including the need to understand and respond to the possible dangers (Stocker et al., 2013). Since the past is the key to the present and the future, the study of past temperature changes is becoming increasingly important for improving our ability to predict the long-term trends of regional and global climate change, and to explore the relationship between climate change and human society.

East Asia, a densely populated region, has attracted much research attention focused on documenting the frequency and amplitude of past climate changes. While the Holocene variability of the precipitation associated with the East Asian summer monsoon (EASM) has been discussed in detail (e.g., Hu et al., 2008; Cai et al., 2010; F.H. Chen et al., 2015; J.B. Liu et al., 2015; J.H. Chen et al., 2016; J.B. Liu et al., 2017), studies of temperature change on different temporal and spatial scales may provide deeper insights to past climate fluctuations and facilitate the prediction of future climate change. During the past few decades, various studies have reconstructed temperature change on different time-scales in northern China, using for example pollen (e.g., Xu et al., 2010; Wen et al., 2010), glycerol dialkyl glycerol tetraethers (GDGTs) (e.g., Gao et al., 2012; Jia et al., 2013; Peterse et al., 2014), stalagmites (Tan et al., 2003), and historical archives (Ge et al., 2003). However, many of these temperature records have significant limitations: for example, pollen assemblages are regarded as a precipitation indicator in many records in northern China (e.g., F.H. Chen et al., 2015; Zhao et al., 2010), the resolution of GDGTs records is too low (although their environmental significance is relatively unambiguous), and the timescales of the stalagmite records from Shihua Cave, and of historical documents from East China, are too short, even if they are accurately dated. All these factors impede our understanding of paleotemperature variability during the Holocene, and in addition there is a mismatch between model simulations of a cooler-than-baseline annual temperature series during the late Holocene compared to the present climate (Jiang et al., 2012) and multi-proxy reconstructions of the mid-Holocene megathermal in China (e.g., Shi et al., 1993; S. Wang et al., 2001; Peterse et al, 2011; Huang et al., 2013). Thus, a long-term, high-resolution paleotemperature reconstruction, using an unequivocal proxy with a robust chronology, is needed.

Chironomids, benthic invertebrates, are recognized as a reliable paleotemperature proxy because of their stenotopic and environmentally-sensitive characteristics (Walker et al., 1991; Levesque et al., 1997; Brooks et al., 2007; Brooks et al., 2012a). Many modern chironomid training sets have been established and used for paleoenvironmental reconstruction (especially paleotemperature) worldwide (e.g., Walker and Cwynar, 2006; Rees et al., 2008; Eggermont et al., 2010; Heiri et al., 2011; Nazarova et al., 2011; Massaferro and Larocque-Tobler, 2013). The paleoenvironmental application of chironomid analysis is relatively recent in China, and studies have concentrated mainly on lake ecology, including analysis of total phosphorus in the middle and lower reaches of the Yangtze River (E.L. Zhang et al., 2006), salinity on the Tibetan Plateau (E.L. Zhang et al., 2007; J.H. Chen et al., 2009), lake water-depth in the arid region of northwest China (J.H. Chen et al., 2014), and precipitation near the EASM boundary (H.P. Wang et al., 2016). Currently, there is only one chironomid-based temperature record, which was obtained from the southeastern Tibetan Plateau (E.L. Zhang et al., 2017a and 2017b).

Here, we present the results of a study of chironomid assemblages in a sediment core from Gonghai Lake in northern China, with the aim of reconstructing regional temperature variability during the past 4000 years in northern China. Gonghai Lake, a freshwater closed-basin lake in Shanxi Province (Fig. 1a), was previously shown to be suitable for chironomid studies (H.P. Wang et al., 2016). A modern calibration data set consisting of 44 fresh water bodies in the area has been developed by H.P. Wang and co-workers (2016). Although this data set suggested that chironomid assemblages in the region responded significantly to fluctuations in water depth since the last deglaciation (H.P. Wang et al., 2016), the existence of several typical stenothermal species (e.g., *Hydrobaenus conformis*-type, *Dicrotendipes nervosus*-type) in the fossil sequence (H.P. Wang et al., 2016), which are sensitive to temperature variability on various time scales (Cranston et al., 1983; Brodin, 1986;

Watson et al., 2010; Brooks and Heiri, 2013), offers great potential for paleotemperature reconstruction in the area. In addition, as well as having significant regional environmental effects, past climate change may also have triggered human societal crises (D.D. Zhang et al., 2015). Numerous studies have demonstrated a strong temporal relationship between societal crises and climate change, and a recent study indicated that climate change (especially temperature) was the ultimate cause of a large-scale human crisis in preindustrial Europe and the Northern Hemisphere (D.D. Zhang et al., 2011). However, most of the previous research has focused on the human societal response to climate change on a large spatial scale (e.g., Tan et al., 2011a) and the response on a regional scale has rarely been considered. The aim of the present study is to reconstruct temperature changes during the past 4000 years in northern China using stenothermic chironomid taxa, and to test the hypothesis that human societal crises were an indirect consequence of temperature fluctuations at the regional scale. Therefore, we (i) identify typical warm- and cold-preference chironomid taxa as temperature indicators, based on the modern calibration set and previous ecological understanding from the literature; (ii) estimate past temperature variability by analyzing the percentage changes in warm- and cold-preference taxa, and validate its reliability; and (iii) compare the temperature record with the documented occurrence of wars in Shanxi Province.

2 Regional setting

Gonghai Lake (38°54’ N, 112°14’ E; 1,860 m.a.s.l), an alpine freshwater lake, is situated on the northeastern margin of the Chinese Loess Plateau (Fig. 1a). The lake is oval-shaped and has a surface area of ~0.36 km^2, a maximum water depth of around 10 m, and a flat bottom-topography (Fig. 1b). The lake may have been formed by tectonic activity at around ~16 ka BP (X. Wang et al., 2014). On average, 77 % of the 445 mm of modern annual precipitation occurs from June to September and is the major water source since the lake is hydrologically closed. Modern mean monthly temperature in the region ranges between -14 °C and +23 °C. In 2009, a 9.42-m-long sediment core (GH09B) was taken in a water depth of 8.96 m (Fig. 1b) using a Uwitec Piston Corer. The core was sliced at 1-cm intervals, freeze-dried and stored at 4 °C in the laboratory. In the present study, 109 samples from the upper 541 cm were processed for chironomid analysis. Several adjacent samples which produced fewer than 30 head capsules were amalgamated. A total of 63 samples was included and used for temperature analysis, of which 44 samples contained more than 40 head capsules and 19 samples contained 30-40 head capsules, representing time intervals varying between 50 and 100 years and spanning the past ca. 4000 years.

Figure 1

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3 Chronology

The age-depth model for Gonghai Lake core GH09B (F.H. Chen et al., 2015) was used in this study. Figure 2 shows the chronology for the last 4000 years. In the age-depth model for core GH09B, 25 accelerator mass spectrometry (AMS) ^{14}C dates were obtained from terrestrial plant macrofossils, calibrated using the IntCal09 calibration curve (Reimer et al., 2009), and used for Bayesian age-depth modelling (Bronk Ramsey, 2008).

Figure 2

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4 Materials and methods

4.1 Chironomid samples

For each sample, chironomid remains were extracted from 1-5 g of freeze-dried sediment. The preparation procedure followed the standard techniques described in Brooks *et al*. (2007). The sediments were deflocculated in warm 10 % KOH for about 15 minutes, and then sieved with 212 μm and 90 μm mesh sieves. Head capsules were hand-picked from the sieve residues under a stereomicroscope at ×20-40 magnification, and mounted on slides, ventral side up, in Hydromatrix beneath a 6-mm coverslip. Chironomid head capsules were identified to the highest possible taxonomic resolution under a compound microscope at ×100-400 magnification with reference to Wiederholm (1983), Rieradevall and Brooks (2001), Brooks *et al*. (2007), Walker (2007), and the chironomid collections housed at the Natural History Museum, London.

4.2 Calibration set

The modern calibration set from around Gonghai Lake obtained by H.P. Wang and coworkers (2016) was used to identify temperature-sensitive chironomid taxa in the region. The data set comprises 44 water bodies in northern China (Fig. 3a), samples from only 30 of which contained sufficient chironomid head capsules for analysis.

Mean annual temperature (TANN), mean summer temperature (summer Tem), and the mean temperatures for June (June Tem), July (July Tem) and August (August Tem) were interpolated from meteorological data from 2001-2011 (Dataset of monthly values of climate data from Chinese surface station, 2017; Zhao et al., unpublished data). It should be noted that the surface of Gonghai Lake freezes in winter which disrupts the linear relationship between water temperature and air temperature. Moreover, the winter season is not the growing season of chironomids (Armitage et al., 1995), and therefore the mean temperature of the winter months was not included in the numerical analysis.

4.3 Historical documentary evidence

A large amount of detailed documentary evidence is available for China. This material documents a wide range of human activities and it provides a valuable reference for the present study. Information pertaining to wars was obtained from the *Tabulation of Wars in Ancient China*, an appendix of the *Military History of China*, which was summarized by the Editorial Committee of Chinese Military History (1985); it has been widely utilized in previous research (D.D. Zhang et al., 2005, 2015). Only the ancient wars which occurred within the current territory of Shanxi Province were counted in the present study. In addition, fluctuations in population size are a major component of human societal evolution and therefore population information was also collated and used to characterize social change. Data documenting fluctuations in the population size of Shanxi Province were obtained from Lu and Teng (2006).

4.4 Numerical analysis

Only taxa which were present in at least two samples with an abundance of >2 % were selected for analysis. A chironomid percentage diagram was plotted using Tilia 2.0.2 (Grimm, 2004). Zonation of the chironomid assemblages was accomplished using stratigraphically-constrained cluster analysis (CONISS) in Tilia 2.0.2 (Grimm, 2004). Both redundancy analysis (RDA) and detrended correspondence analysis (DCA) were performed using R 3.2.1 (Team, 2014) to explore the relationship between modern chironomid taxa and temperature variables, and to analyze the distribution characteristics of fossil assemblages, respectively. In addition, Pearson correlation and Granger causality analysis were performed to explore the relationship between climate change and the occurrence of wars.

5 Results

5.1 Modern chironomid assemblages

Air temperature is widely assumed to play a key role in controlling the abundance and composition of chironomid taxa in freshwater (e.g., Walker, 2001; Brooks, 2003; Walker and Cwynar, 2006). RDA of the chironomid taxa and temperature variables shows that TANN tends to be more significant in influencing the chironomid assemblages than the mean temperatures of summer, June, July and August (Fig. 3b). This result also passed the Monte Carlo permutation test (p=0.001) even though the explanatory ability is relatively low (Fig. 3b). The taxa are plotted in Fig. 3c according to the taxon scores in the RDA of chironomid assemblages and TANN. Taxa on the left side of the plot currently prefer a warmer environment in the Gonghai Lake region because they are distributed close to the positive axis of TANN in Fig. 3b; conversely, those taxa on the right side of the plot prefer a colder environment.

The following criteria were used to identify temperature-sensitive species: (1) Those located at the ends of Fig. 3c, and (2) those species previously reported as warm or cold stenotherms. On the left side of the diagram, *Polypedilum nubifer*-type, *Dicrotendipes nervosus*-type and *Tanytarsus mendax*-type have been previously reported as warm stenotherms (Watson et al., 2010; Brooks and Heiri, 2013), and were defined as thermophilous taxa here. *Procladius choreus*-type and *Microchironomus* were eliminated because their high scores on the positive axis may be because in the Gonghai Lake region they are indicators of deep water (H.P. Wang et al., 2016). On the right side of the diagram, *Hydrobaenus conformis*-type, *Psectrocladius sordidellus*-type, and Chironomini 1st instar (probably *Sergentia coracina*-type) have been widely regarded as cold stenotherms (Cranston et al., 1983; Brodin, 1986; Brooks and Heiri, 2013), and were defined as cold-water taxa here. *Chironomus gonghai*-type was included given that it was located at the end of the diagram and tends to live in cold environments (see Fig. 5 in H.P. Wang et al., 2016).

Figure 3

5.2 Chironomid assemblages in Gonghai Lake

44 major taxa within 25 genera and 4 subfamilies (Tanypodinae, Chironomini, Tanytarsini and Orthocladiinae) were identified, and 3 chironomid assemblage zones were recognized (Fig. 4). 95.7% of the chironomid head capsules were identified to genus or species morphotype. Due to poor preservation, the remaining 4.3% were only identified to subfamily level; this was especially applicable to the head capsules of the tribe Tanypodinae because the key identification segments of fragmented subfossils were often covered by other material. The concentration of chironomid head capsules appeared to follow variations in the organic

matter content of the samples. The concentration was high before 1500 cal yr BP and then decreased to very low values until the present (Fig. 4). The chironomid assemblage zones are described below.

Zone 1 (ca. 4000-2700 cal yr BP). This zone is dominated by *Cladotanytarsus mancus*-type, *Procladius* and *Stictochironomus*. Many Tanytarsini taxa, including *Tanytarsus* 'no spur', *Tanytarsus mendax*-type, *Tanytarsus lugens*-type and *Tanytarsus glabrescens*-type, are present at a low abundance.

Zone 2 (ca. 2700-1270 cal yr BP). This zone is characterized by the rapid decrease in the abundance of *Cladotanytarsus mancus*-type and by the sudden appearance of *Parakiefferiella bathophila*-type. In addition, there is an increasing representation of *Paratanytarsus*, *Hydrobaenus conformis*-type and *Psectrocladius sordidellus*-type.

Zone 3 (ca. 1270-present). This zone is characterized by a significant increase in *Cladotanytarsus mancus*-type and a decrease in *Parakiefferiella bathophila*-type. *Hydrobaenus conformis*-type remains at a relatively high level throughout the zone. There are large fluctuations in the representation of most of the taxa and therefore the zone is divided into the following subzones.

Subzone 3a (ca. 1270-1040 cal yr BP). This subzone is characterised by an abrupt increase of *Cladotanytarsus mancus*-type and decrease of *Parakiefferiella bathophila*-type.

Subzone 3b (ca. 1040-970 cal yr BP). This subzone, which only consists of two samples, is dominated by *Propsilocerus jacuticus*-type, *Chironomus gonghai*-type, Chironomini *larvula* (probably *Sergentia coracina*-type) and *Procladius*.

Subzone 3c (ca. 970-570 cal yr BP). Although they are very poorly represented in the previous subzone, *Cladotanytarsus mancus*-type, *Parakiefferiella bathophila*-type and

Hydrobaenus conformis-type became dominant in this subzone.

Subzone 3d (ca. 570-270 cal yr BP). In this subzone, *Psectrocladius sordidellus*-type increases abruptly and reaches its maximum abundance, and *Hydrobaenus conformis*-type is highly abundant throughout.

Subzone 3e (ca. 270 cal yr BP-present). The dominant taxon in this subzone is *Paratanytarsus penicillatus*-type. Both *Cladotanytarsus mancus*-type and *Glyptotendipes severini*-type increase slightly, whereas *Hydrobaenus conformis*-type and *Psectrocladius sordidellus*-type decrease significantly.

Figure 4

5.3 Changes in the abundance of temperature indicator species

Based on the definition of warm- and cold-preference taxa given above, their totals were calculated to reconstruct temperature changes during the past 4000 years (Fig. 4). The results indicate an overall trend of decreasing temperature; furthermore, fluctuations in the abundance of cold-preference taxa indicate that the temperature was high in zone 1, decreased sharply around 2700 cal yr BP but remained relatively high in zone 2, and fluctuated significantly and reached a minimum in zone 3. It should be noted that the abundance of warm-preference taxa is much less than that of cold-preference taxa, and the former were often absent during the past 2700 years (Fig. 4). To avoid the potential limitations of presence/absence data, the changes in abundance of cold-preference taxa (which provide more detailed information about temperature variations on a centennial timescale) were primarily used to investigate temperature changes.

5.4 Wars and population changes

We calculated a total of 418 wars from 718 BC to 1911 AD. Given that the resolution of the Gonghai Lake samples ranges from 50-100 years, the incidences of wars were summed to produce a 50 year-resolution. The record of chironomid-inferred temperature variability (Fig. 5a) and the pollen-based precipitation reconstruction for Gonghai Lake (Fig. 5b; F.H. Chen et al., 2015) were compared with the cumulative frequency of these events (Fig. 5c). The distribution of wars reveals that they occurred more frequently when temperature and precipitation decreased abruptly, and they also lasted for a relatively long time (Fig. 5c). For example, these events were the most severe during the Little Ice Age (LIA) when both the temperature and precipitation decreased significantly, which lasted for nearly 350 years. The results of Pearson correlation and Granger causality analysis show that the change in abundance of the cold-preference taxa are significantly related to the incidence of wars ($r=-0.189$ in Table 1, $p<0.01$ in Table 2).

Only 19 records of population size in Shanxi Province since 340 BC are mentioned in Lu and Teng (2006), and they were used in the present study. These data are evenly distributed within each dynasty (Fig. 5d). Although the population size fluctuated significantly, an overall increasing trend is evident, together with frequent population collapses following intervals with a significant number of wars.

Figure 5

Table 1

Table 2

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6 Discussion

6.1 Effects of temperature on the modern and fossil chironomids in the Gonghai Lake region

Relevant physical, chemical and climatic variables were all included in the investigation of the relationships between chironomid assemblages and environmental parameters in the Gonghai Lake region (H.P. Wang et al., 2016). Although previous analysis indicated that the fossil chironomids mainly responded to changes in precipitation through water depth since the last deglaciation (H.P. Wang et al., 2016), the existence of certain typical stenothermic taxa provides a high potential for extracting a temperature signal. To further verify whether the stenothermic taxa (based on the published literature) also have a thermal significance in the Gonghai Lake region, the temperature variables (TANN, summer Tem, June Tem, July Tem and August Tem) were used as the only variables to constrain the changes in the abundance of the taxa in the calibration set. The results of RDA of modern chironomid assemblages and temperature variables (Fig. 3b), as well as the Monte Carlo permutation test, demonstrate that TANN was a significant environmental variable influencing the modern chironomid taxa. In addition, TANN has a higher score on the first axes than the other variables in Fig. 3b, furthermore, TANN was the only variable selected in the interactive-forward-selection (p=0.026). This result has rarely been observed in the published literature, although it has been noted that chironomids often respond significantly to mean July or summer temperature (e.g., Brooks and Birks, 2001; Self et al., 2011; Samartin et al., 2017). Our observed correlation between modern chironomid assemblages and TANN provides a valuable reference for extracting temperature signals from the fossil chironomid assemblages of Gonghai Lake. For example, *Chironomus gonghai*-type is ranked at the end of the RDA of the modern assemblage data and TANN, indicating that it is cold-temperature indicator in the Gonghai Lake region. Moreover, this taxon was abundant during the Younger Dryas, clearly indicating that it prefers a cold environment. However, *Chironomus* is reported as a temperate indicator in chironomid records from Scotland and northern Russia (e.g., Brooks et al., 2007; Brooks et al., 2012b; Nazarova et al., 2015). The reason for these contradictory findings may be that *Chironomus gonghai*-type is a new species, or that *Chironomus* has a different preference in the Gonghai Lake region. These observations indicate that it is necessary to improve the taxonomic resolution of chironomid identifications and to establish more precisely the environmental preferences of chironomid taxa from local training sets to enhance the reliability of paleotemperature reconstructions.

6.2 Faunistics and inferred temperature change

Temperature variability in the Gonghai Lake region during the past 4000 years is revealed by changes in the abundance of the warm-preference and cold-preference chironomid taxa (Fig. 4). As described in section 5.3, the variations in the abundance of the cold-preference taxa were primarily used to investigate the temperature changes. An explanation for the more resolved temperature signal carried by the cold-preference taxa may be that they were easily able to become dominant in Gonghai Lake and respond quickly to temperature fluctuations due to the lake's relatively high-elevation (1860 m a.s.l.) and the decreasing trend of late Holocene temperature.

In addition to the warm- and cold-preference taxa, there are other chironomid taxa in the Gonghai Lake record which could also be regarded as temperature indicators (although to a significantly lesser extent) and it is worth investigating whether they exhibit a similar trend of temperature change to the warm- and cold-preference taxa. Details of the faunistics and inferred environmental change for each of the three intervals of the record are given below.

4000-2700 cal yr BP. During this interval, the temperate-preferring taxon *Cladotanytarsus mancus*-type (Brooks, 2006) is dominant. Thus, we infer that the temperature was relatively high during this interval. *Stictochironomus* and *Procladius* were abundant in this stage as well as in the mid-Holocene (H.P. Wang et al., 2016), and this may indicate a relatively warm environment in this stage. This is similar to a record from Norway which showed that *Stictochironomus* and *Procladius* indicate a relatively warm environment (Brooks and Birks, 2000).

2700-1270 cal yr BP. The abundance of the previously dominant temperate-preference *Cladotanytarsus mancus*-type decreased abruptly and it was replaced by *Parakiefferiella bathophila*-type which is also a temperate-preference taxon (Brooks and Birks, 2000; Brooks, 2000). This shift in the representation of the dominant temperate-preference taxa probably occurred in the context of cold conditions, because the cold stenotherm *Hydrobaenus conformis*-type (Cranston et al., 1983) appears for the first time. In addition, another cold indicator, *Psectrocladius sordidellus*-type (Brooks and Heiri, 2013), also started to increase, marking the beginning of the 2700 cal yr BP cold event. However, the abundance of

Paratanytarsus penicillatus-type, which is not usually indicative of cool temperatures, also increased since 2700 cal yr BP, simultaneously with *Psectrocladius sordidellus*-type. This curious combination of chironomid changes also occurred in a sediment record from Gerzensee, Switzerland (Brooks and Heiri, 2013). Overall, we infer that temperature began to decrease during this second stage.

1270 cal yr BP-present. The cold-preference taxa, including *Hydrobaenus conformis*-type and *Psectrocladius sordidellus*-type, and cool-preference taxa *Paratanytarsus penicillatus*-type, are dominant in this stage, while the relatively temperate-preference taxa, including *Cladotanytarsus mancus*-type, *Parakiefferiella bathophila*-type and *Procladius*, exhibit low abundances. Thus, we conclude that temperatures reached a minimum. Several climatic events can be recognized; for example, chironomid subzones 3a, 3c and 3e correspond to the Sui-Tang Warm Period (STWP), the Medieval Warm Period (MWP) and the modern warm period, respectively; in addition, subzones 3b and 3d correspond to the cold periods of the 5 Dynasties & 10 Kingdoms in China and the LIA, respectively.

The foregoing analysis indicates that the temperature variability inferred from typical chironomid temperature-indicators is in accord with that inferred from most of the other taxa in the Gonghai Lake sediments, which supports our reconstruction.

In addition, a recent study indicated that the organic matter content of the Gonghai Lake sediments was dominated by the authigenic fraction during the past 4000 years (S.Q. Chen et al., under review). This suggests that most of the organic matter is of within-lake origin (Birks and Birks, 2006) and thus that variations in its content probably reflect past regional temperature changes. The variation of the organic content of the Gonghai Lake sediments (Fig. 4; S.Q. Chen et al., 2018) is consistent with the decreasing trend of chironomid-inferred temperature, validating the reliability of our temperature reconstruction.

6.3 Intraregional temperature comparison

As mentioned previously, climate-model simulation results indicate that TANN in China was higher in the late-Holocene than in the mid-Holocene (Jiang et al., 2012). In addition, even the global TANN indicates a warming trend from the early Holocene onwards, due to the retreating ice sheets and rising atmospheric greenhouse gas concentrations (Z. Liu et al., 2014), in contradiction to the cooling trend inferred from various proxy records for 30-90N (Marcott et al., 2013). Our qualitative reconstruction of TANN in North China suggests that the warming trend estimated for the late Holocene by the simulation results is not convincing.

To validate our chironomid-inferred temperature record (Fig. 6a), all the Holocene temperature reconstructions for China were collected. However, as mentioned in the **Introduction**, many of the records are problematic in that they have a large dating uncertainty, low resolution or are environmentally ambiguous; for these reasons, they were excluded. Only two unambiguous and high-resolution temperature reconstructions were finally chosen for further comparison due to their precise high-quality dating which was the most important selection criterion used in this study. The first record is based on stalagmite layer thickness at Shihua Cave, close to Gonghai Lake (Tan et al., 2003) (Fig. 6b); and the second is based on historical documents pertaining to winter temperature changes in Eastern China (Ge et al., 2003) (Fig. 6c). The three records exhibit a consistent pattern of temperature change on both a millennial and shorter scale: cold intervals from 1350-1650 cal yr BP, 950-1150 cal yr BP and 300-650 cal yr BP (LIA); and warm intervals from 1150-1350 cal yr BP (STWP) and 650-950 cal yr BP (MWP). In addition, an integrated temperature record for the whole of China, produced by combining multiple paleoclimate proxy records from ice cores, tree rings, lake sediments and historical documents (Fig. 6d, Yang et al., 2002), was compared with the chironomid-inferred temperature record from Gonghai Lake. Both records show the same pattern of warm and cold intervals during the past 2000 years: for example, the cold intervals of 1350-1650 cal yr BP and 950-1150 cal yr BP, and the LIA, STWP, MWP and modern warm periods.

In addition to the consistency of the records described above, the trend of generally decreasing temperature during the past 4000 years is also evident in several other recent proxy-based reconstructions: for example, the $U^{K'}_{37}$ record from the sediments of Gahai and Qinghai Lakes in the northeastern Tibetan Plateau (He et al., 2013; Z. Wang et al., 2015), a novel microbial lipid record from Dajiuhu in central China (Huang et al., 2013), percentages of thermophilous trees in Huguangyan Maar Lake in southern China (S.Y. Wang et al., 2007), and an integrated temperature reconstruction for 30°-90° in the Northern Hemisphere (Fig. 6e) (Marcott et al., 2013). The similarity of these proxy-based temperature reconstructions to a record of total solar irradiance (Fig. 6f; Steinhilber et al., 2009) and the similar decreasing trend of the various reconstructions and solar insolation (Fig. 6g; Berger and Loutre, 1991) suggest that solar irradiance and insolation are important external drivers of temperature variability during the late Holocene at centennial and millennial scales, respectively.

The foregoing demonstrates that our chironomid-based temperature reconstruction is reasonable and representative and that the approach can be extended to longer time-scales. The success of our approach can be attributed to the following factors: (i) Chironomids are sensitive to temperature changes; (ii) the precise, high-resolution chronology increases the usefulness of the temperature reconstruction; and (iii) the 60 a-resolution enables the results to be compared with other high-quality temperature reconstructions and with documentary evidence. Furthermore, our results, combined with a pollen-based precipitation reconstruction from the same core, enable the identification of trends in both temperature and humidity (Fig. 5b; F.H. Chen et al., 2015). Generally, there were pronounced changes in warm and humid/cool and dry climatic patterns both on millennial- and centennial- scales in the Gonghai Lake region, which is consistent with a previous synthesis study (Tan et al., 2011b). However, this pattern is not evident during the last 300 years (Fig. 5). Given the general consistency between our temperature reconstruction and other records in this period (such as the rapid warming at the end of LIA, Fig. 6), more high-quality precipitation records are needed to further validate this warm and dry configuration.

Figure 6

6.4 Relationship between societal crises in Shanxi Province and climate change

Although past wars in China were often the consequence of social-geopolitical factors, including territorial disputes (Zhao, 2006), nomadic invasions, and agricultural expansion (Di Cosmo, 2002), the impact of climate change should also be considered when analyzing societal evolution (Ge, 2011). Traditionally, China was an agricultural society the productivity of which was very low during most of its history. When temperature or precipitation decreased abruptly, or fluctuated significantly, there tended to be an increase in the incidence of natural disasters such as floods and droughts (Q. Zhang et al., 2008) which seriously affected agricultural production. The combination of a large population and a poor grain harvest often resulted in high rice prices and famines, which generated large numbers of homeless refugees and outbreaks of plague. These factors would finally trigger wars and social unrest which acted to reduce the population size. To analyze the societal response in Shanxi Province to climate change, the occurrence of wars (Fig. 5c) and changes in population size (Fig. 5d) were summarized for comparison with the chironomid-inferred temperature record (Fig. 5a) and the pollen-based precipitation reconstruction (Fig. 5b; F.H. Chen et al., 2015) from Gonghai Lake.

Although both temperature and precipitation in the Gonghai Lake region exhibit a decreasing trend during the last 4000 years, temperature changes were not always in phase with precipitation changes. For example, four cold events can be recognized from the chironomid-inferred temperature record (Fig. 5a), which occurred during ~2180-2710 cal yr BP (Spring & Autumn and Warring States Period), 1300-1690 cal yr BP (Era of Disunity), 900-1050 cal yr BP (5 Dynasties and 10 Kingdoms), and 300-650 cal yr BP (Ming Dynasty). The reconstructed precipitation record only exhibits two dry events during this interval, from 900-1050 cal yr BP and from 300-650 cal yr BP. The societal response to such events varied during different periods. The incidence of war was especially high during 900-1050 cal yr BP and 300-650 cal yr BP when both temperature and precipitation were lower; it was higher at these times than during the periods of 2180-2710 cal yr BP and 1350-1690 cal yr BP when the decrease in temperature was more severe than that of precipitation. This relationship is confirmed by the results of Granger causality analysis (see Table 2 in *War and population*), which show that the incidence of wars is more strongly correlated with temperature changes than with precipitation. However, this may only be a statistical artifact and the causal relationship between climate change and societal crises needs to be further tested in future research. A sharp decrease in temperature may have been an important precondition for an outbreak of war in China, but it may have insufficient in isolation, and decreases in precipitation during the past 3000 years may also have been important. Moreover, the fact that historical documents in China became increasingly detailed and reliable as human society developed (Ge et al., 2010) may be an additional explanation for the observation that increases in the frequency of wars persistently coincided with decreases in temperature and precipitation. With regard to population, an increase often occurred during warm periods which would have created latent economic pressures when the crop harvest was poor following a cold period. In addition, population collapse often occurred following an increase in the frequency of wars, famines and plagues during cold periods, suggesting that population size could be indirectly influenced by climate change (D.D. Zhang et al., 2011).

The demise of the Ming dynasty provides an example of how climatic deterioration, as well as the related socioeconomic impacts, severely undermined an empire in historical China. The late Ming (306-390 cal yr BP) coincided with the Little Ice Age, when temperatures decreased significantly (Fig. 5a). During this cold period, the incidence of natural disasters such as flood and droughts was the highest in Shanxi history (G.Y. Chen, 1939). Rapid cooling accompanied by large-scale desertification began in the 1620s and had a devastating effect on agricultural production (X. Wang et al., 2010; Yin et al., 2015). Zheng *et al.* (2014) noted that the total grain yield in Shanxi in the 1630s ranged from 1219.8×10^6 to 1951.3×10^6 kg, a reduction of almost 50% compared to the yield of ~1580 (2439.1×10^6 kg). The population increased from 8.42 to 9.50 million during this period (Zheng et al., 2014) and it seemed that widespread famines would be unavoidable given the additional factor that governmental disaster relief malfunctioned due to political corruption in the late Ming (Zheng et al., 2014; Xiao et al., 2015). Furthermore, the fiscal situation of the Ming was precarious since conflicts with the Jurchen people soon exhausted the treasury and the government was forced to levy higher taxes on the peasants (Huang, 1974; Gu, 1984; Wei et al., 2014). The exacerbation of the food crisis consequently triggered a prolonged peasant uprising which broke out in northern Shaanxi, spread to Shanxi, and finally overturned the Ming Empire in 1644. The historical records at a provincial level are voluminous and the socioeconomic context was complex and further research is needed to explore the relationship between climate change and the societal response on a regional scale in China

7 Conclusions

Together with a precise high-resolution chronology and a modern calibration set, we have used chironomid assemblages from the sediments of Gonghai Lake to reconstruct temperature variations during the past 4000 years in northern China. Combined with historical documents, the temperature record was used to explore the relationship between climate change and human societal changes at the regional scale. The principal conclusions are as follows:

(1) The chironomid-inferred temperature record exhibits a stepwise decreasing trend since 4000 cal yr BP. Temperature remained high during 4000-2700 cal yr BP; decreased abruptly around 2700 cal yr BP; decreased gradually from 2700-1270 cal yr BP; and reached a minimum, accompanied by frequent fluctuations, during the last 1270 years. In addition, the cold event, corresponding to the Era of Disunity in China, the STWP, MWP and LIA, revealed in the chironomid record from Gonghai Lake, were also recorded in numerous other multi-proxy records, validating the reliability of our temperature reconstruction.

(2) The frequency of wars in Shanxi Province during the last 2700 years is significantly correlated with the chironomid-inferred temperature record from Gonghai Lake. Reductions in population size, associated with warfare and famine, are also correlated with the temperature fluctuations. We suggest that the impacts of temperature and precipitation on human society should be further studied in the future.

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Table captions

Table 1 Results of Pearson correlation analysis of cold-preference chironomid taxa percentages, reconstructed precipitation and incidence of war.

Table 2 Granger causality analysis of cold-preference chironomid taxa percentages, reconstructed precipitation, and incidence of war.

Table 1

		War
Cold Taxa	Pearson correlation (r)	0.571^{**}
	Significance (p)	0.000
Precipitation	Pearson correlation (r)	-0.214
	Significance (p)	0.125

**. p<0.01 (2-tailed)

Table 2

Null Hypothesis	F	p
COLD TAXA do not Granger Cause WAR	16.4887	0.0002^{**}
PRECIPITATION does not Granger Cause WAR	0.96106	0.3317

**. p<0.01

Figure captions

Figure 1 (a) Location of Gonghai Lake (blue dot) and other temperature records in North China. (b) Location of sediment core GH09B. Mountain (Mid and High) indicates the area above 1000 m.a.s.l. The position of the modern Asian summer monsoon boundary is after F.H. Chen et al. (2010).

Figure 2 Age-depth model for core GH09B (F.H. Chen et al., 2015).

Figure 3 Information about the modern calibration data set obtained from the Gonghai Lake area. (a) Location of modern surface samples (white dots); (b) RDA bi-plot of modern chironomid assemblages and TANN, summer Tem, June Tem, July Tem and August Tem; and (c) relative abundance of modern chironomid assemblages from the modern calibration set (H.P. Wang et al., 2016). All taxa are arranged according to their RDA 1 scores of chironomids and TANN. Only taxa occurring in at least two samples with an abundance of >2 % are plotted.

Figure 4 Relative abundance of the main chironomid taxa from Gonghai Lake during the past 4000 years. Taxa are plotted from left to right in order of their DCA 1 scores. Loss-on-ignition (LOI) values, chironomid concentration, percentages of warm- and cold-preference taxa are plotted as red lines with squares, black bars, and red and blue patterns, respectively. Three chironomid assemblage zones were defined by CONISS results.

Figure 5 Comparison of (a) cold-preference taxa percentages and (b) reconstructed precipitation at Gonghai Lake (F.H. Chen et al., 2015) with (c) frequencies of wars in Shanxi Province, China and (d) population size (in units of 1 million, square dots) of Shanxi Province during the past 2300 years; the data are spline connected. Grey shaded areas indicate cold events.

Figure 6 Comparison of (a) cold-preference taxa percentages in Gonghai Lake with intraregional temperature records during the past 4000 years, including (b) reconstructed temperature based on stalagmite layer thickness in Shihua Cave (Tan et al., 2003), (c) winter half-year temperature anomalies in eastern China with a 30-year resolution (Ge et al., 2003), (d) weighted temperature reconstruction for China obtained by combining multiple paleoclimate proxy records (Yang et al., 2002), (e) and the paleotemperature for 30°-90° of the Northern Hemisphere (Marcott et al., 2013). The higher values from (a) to (e) represent warmer environments, and vice-versa. All the temperature records are compared with (f) a reconstruction of total solar irradiance (Steinhilber et al., 2009) and summer insolation at 65°N (Berger and Loutre, 1991) during the past 4000 years. Grey shaded areas indicate cold events.

Fig. 1

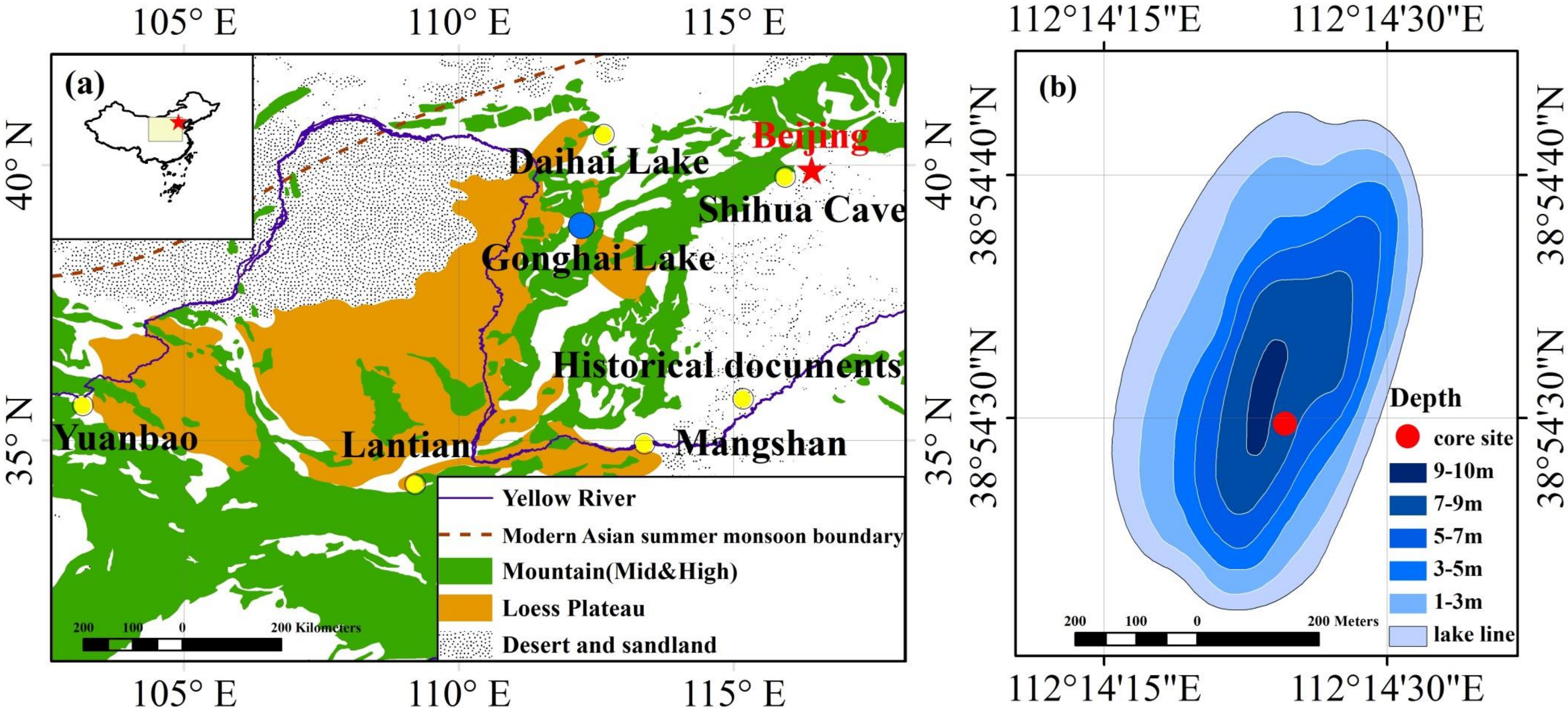

(a)
105° E
110° E
115° E
40° N
35° N
Beijing
Daihai Lake
Shihua Cave
Gonghai Lake
Historical documents
Yuanbao
Lantian
Mangshan
Yellow River
Modern Asian summer monsoon boundary
Mountain(Mid&High)
Loess Plateau
Desert and sandland
200 100 0 200 Kilometers
(b)
112°14'15"E
112°14'30"E
38°54'40"N
38°54'30"N
Depth
core site
9-10m
7-9m
5-7m
3-5m
1-3m
lake line
200 100 0 200 Meters

Fig. 2

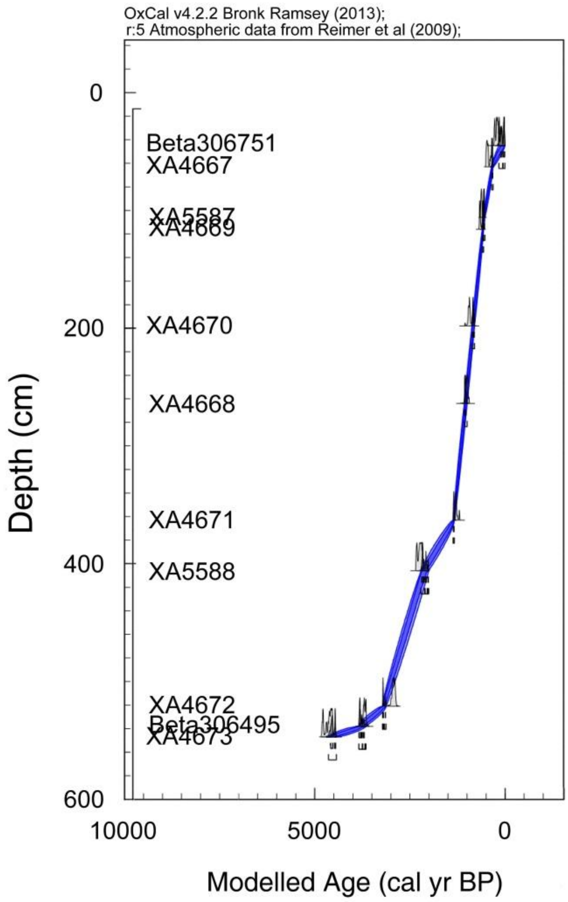

OxCal v4.2.2 Bronk Ramsey (2013);
r:5 Atmospheric data from Reimer et al (2009);
Beta306751
XA4667
XA5587
XA4669
XA4670
XA4668
XA4671
XA5588
XA4672
Beta306495
XA4673
Depth (cm)
0
200
400
600
10000
5000
0
Modelled Age (cal yr BP)

Fig. 3

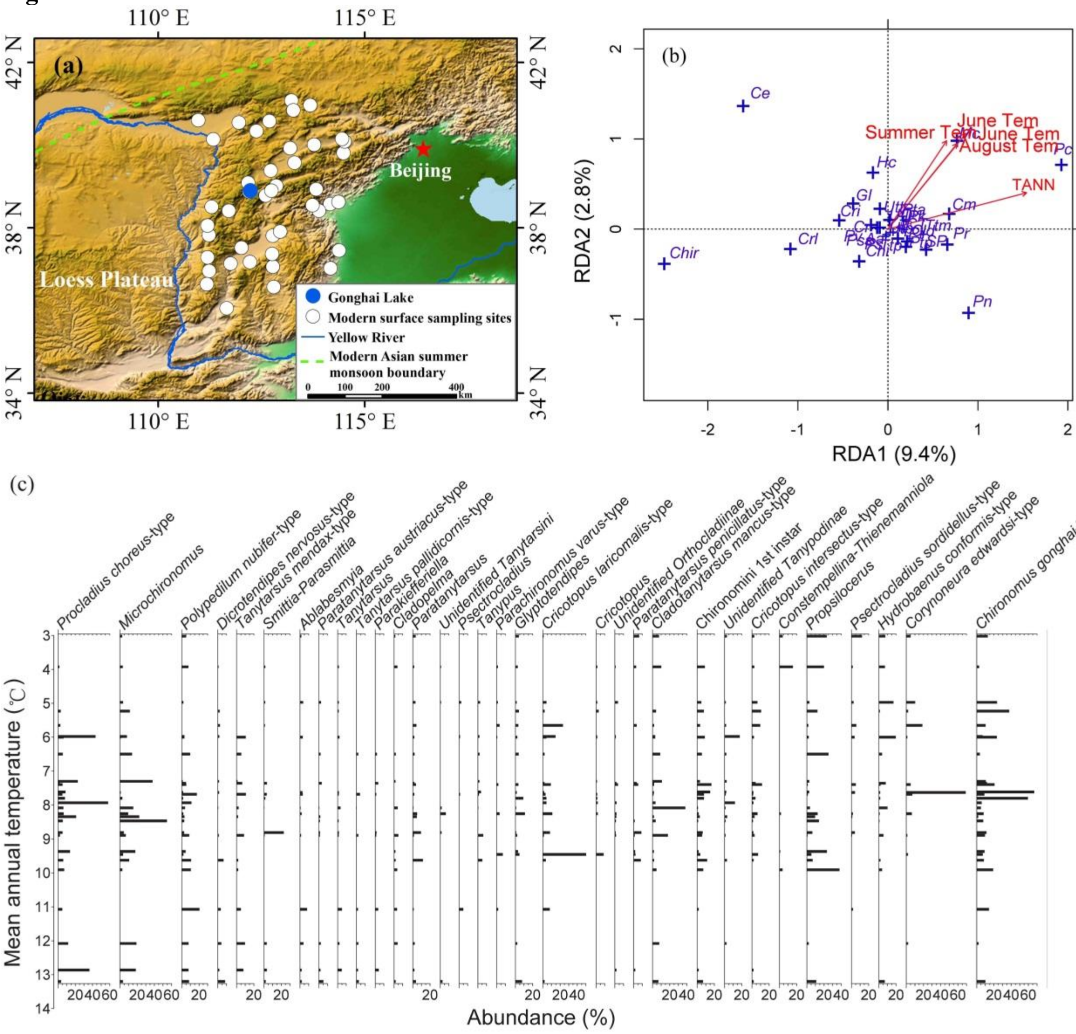

(a)
110° E
115° E
42° N
38° N
34° N
Beijing
Loess Plateau
Gonghai Lake
Modern surface sampling sites
Yellow River
Modern Asian summer monsoon boundary
0 100 200 400 km
(b)
RDA1 (9.4%)
RDA2 (2.8%)
June Tem
Summer Tem
July Tem
August Tem
TANN
Ce
Hc
Gl
Ch
Chir
Crl
Cm
Pr
Pc
Pn
(c)
Procladius choreus-type
Microchironomus
Polypedilum nubifer-type
Dicrotendipes nervosus-type
Tanytarsus mendax-type
Smittia-Parasmittia
Ablabesmyia
Paratanytarsus austriacus-type
Tanytarsus
Tanytarsus pallidicornis-type
Parakiefferiella
Cladopelma
Paratanytarsus
Unidentified Tanytarsini
Psectrocladius
Tanypus
Parachironomus varus-type
Glyptotendipes
Cricotopus laricomalis-type
Cricotopus
Unidentified Orthocladiinae
Paratanytarsus penicillatus-type
Cladotanytarsus mancus-type
Chironomini 1st instar
Unidentified Tanypodinae
Cricotopus intersectus-type
Constempellina-Thienemanniola
Propsilocerus
Psectrocladius sordidellus-type
Hydrobaenus conformis-type
Corynoneura edwardsi-type
Chironomus gonghai-type
Mean annual temperature (℃)
Abundance (%)

Fig. 4

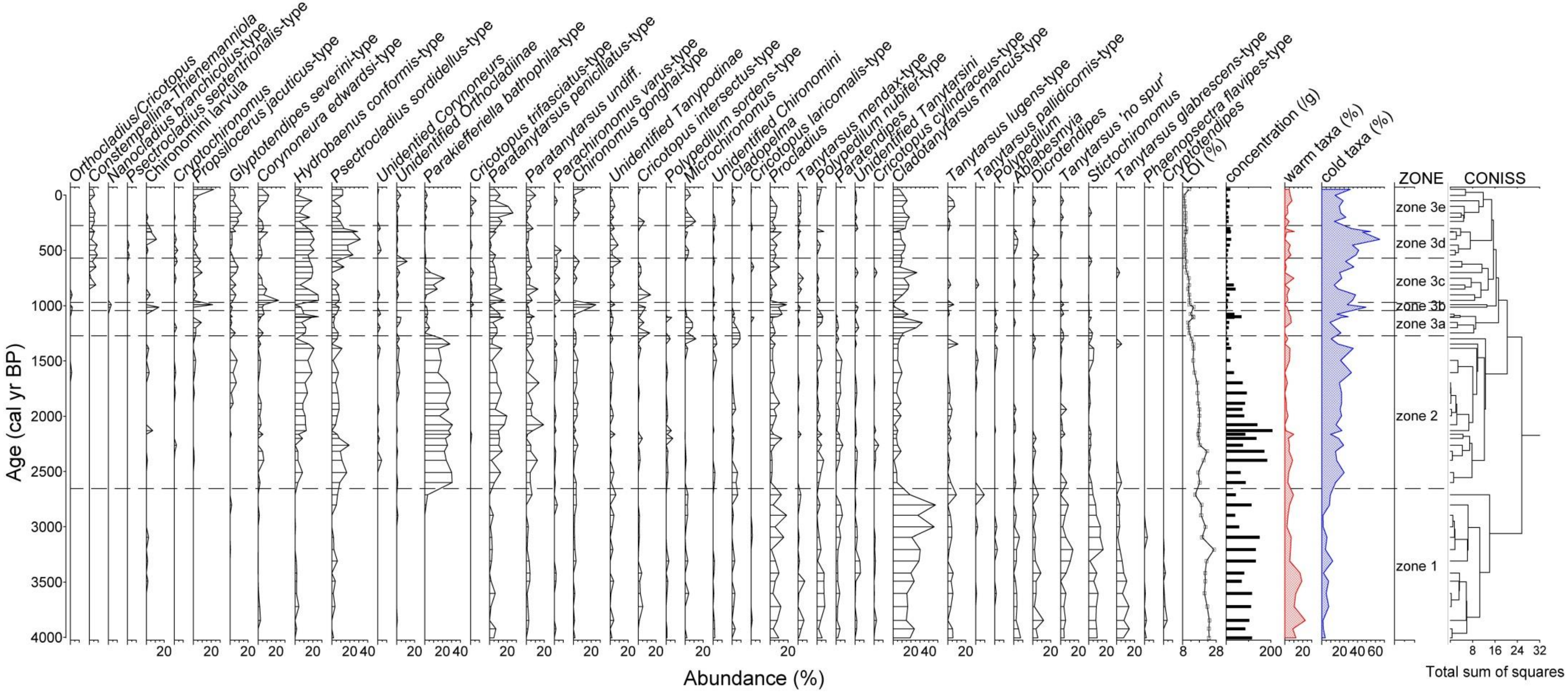
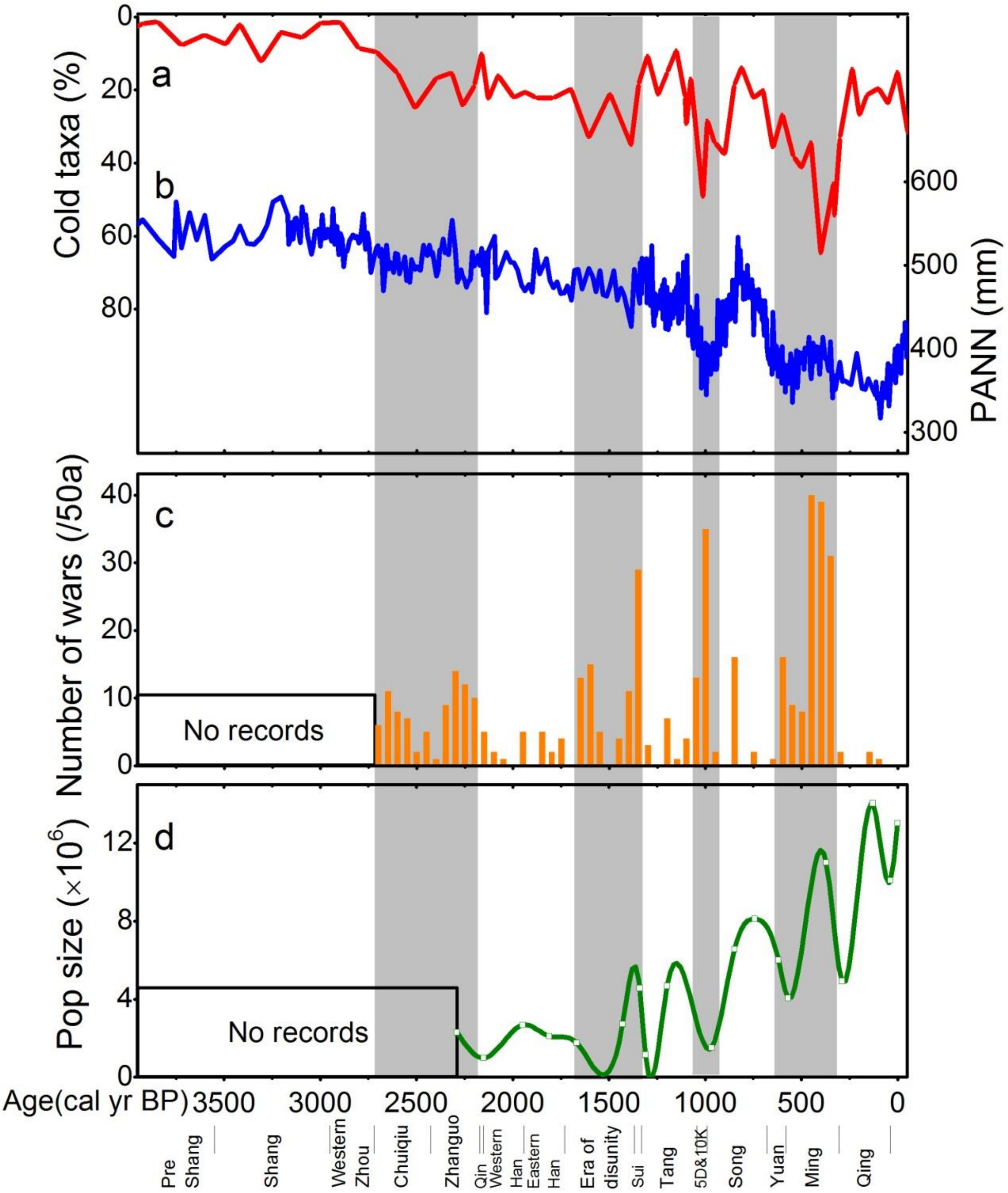
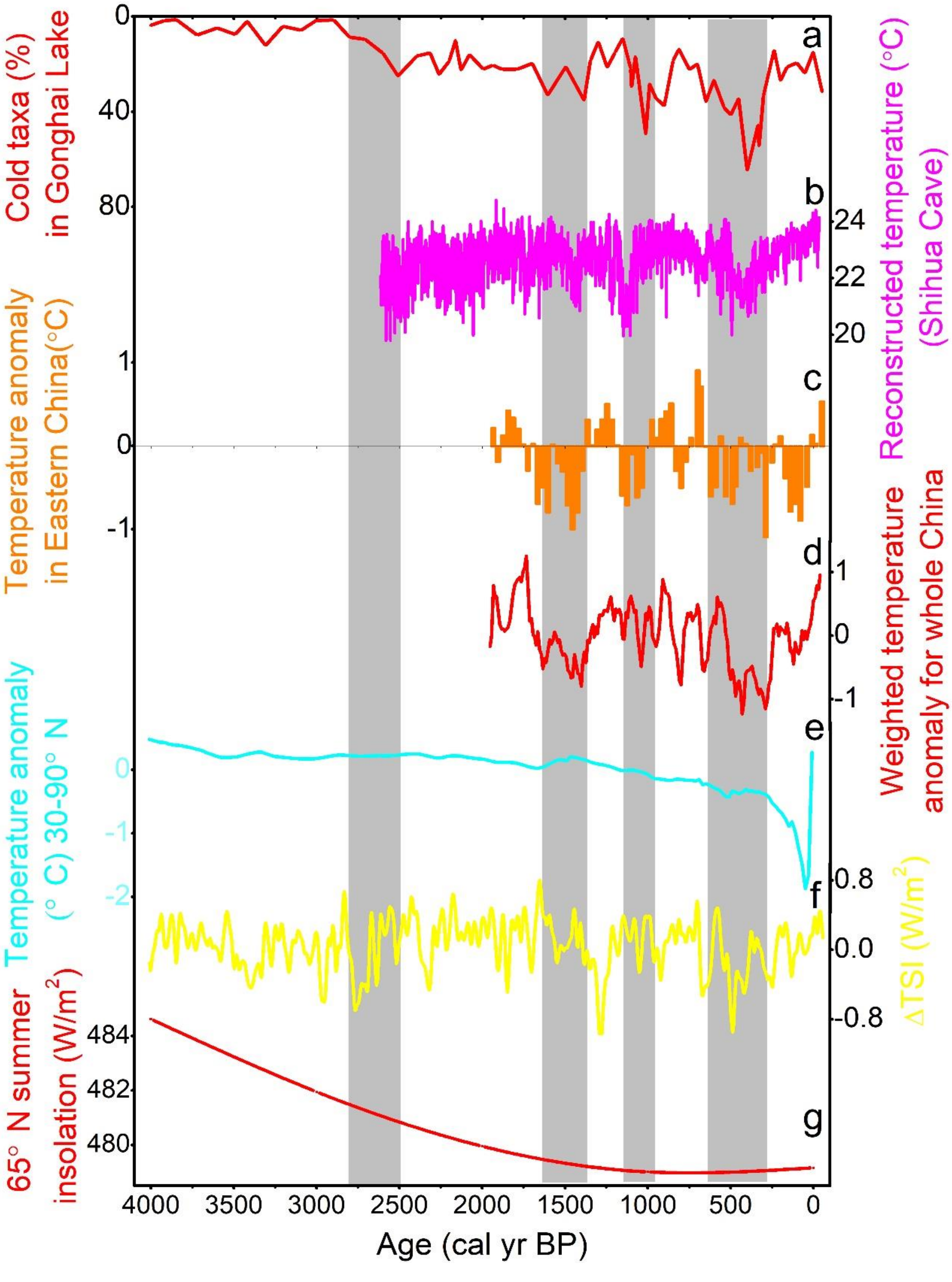

Orthocladius/Cricotopus
Constempellina-Thienemanniola
Nanocladius branchicolus-type
Psectrocladius septentrionalis-type
Chironomini larvula
Cryptochironomus
Propsilocerus jacuticus-type
Glyptotendipes severini-type
Corynoneura edwardsi-type
Hydrobaenus conformis-type
Psectrocladius sordidellus-type
Unidentied Corynoneurs
Unidentified Orthocladiinae
Parakiefferiella bathophila-type
Cricotopus trifasciatus-type
Paratanytarsus penicillatus-type
Paratanytarsus undiff.
Parachironomus varus-type
Chironomus gonghai-type
Unidentified Tanypodinae
Cricotopus intersectus-type
Polypedilum sordens-type
Microchironomus
Unidentified Chironomini
Cladopelma
Cricotopus laricomalis-type
Procladius
Tanytarsus mendax-type
Polypedilum nubifer-type
Paratendipes
Unidentified Tanytarsini
Cricotopus cylindraceus-type
Cladotanytarsus mancus-type
Tanytarsus lugens-type
Tanytarsus pallidicornis-type
Polypedilum
Ablabesmyia
Dicrotendipes
Tanytarsus 'no spur'
Stictochironomus
Tanytarsus glabrescens-type
Phaenopsectra flavipes-type
Cryptotendipes
LOI (%)
concentration (/g)
warm taxa (%)
cold taxa (%)
ZONE
CONISS
zone 3e
zone 3d
zone 3c
zone 3b
zone 3a
zone 2
zone 1
Age (cal yr BP)
Abundance (%)
Total sum of squares

Fig. 5



a
b
c
d
Cold taxa (%)
PANN (mm)
Number of wars (/50a)
Pop size (×10^6)
No records
No records
Age(cal yr BP)
Pre Shang
Shang
Western Zhou
Chuiqiu
Zhanguo
Qin
Western Han
Eastern Han
Era of disunity
Sui
Tang
5D&10K
Song
Yuan
Ming
Qing

834 **Fig. 6**



Cold taxa (%) in Gonghai Lake
0
40
80
a
Reconstructed temperature (°C) (Shihua Cave)
b
24
22
20
Temperature anomaly in Eastern China(°C)
1
0
-1
c
Weighted temperature anomaly for whole China
d
1
0
-1
Temperature anomaly (° C) 30-90° N
e
0
-1
-2
ΔTSI (W/m²)
f
0.8
0.0
-0.8
65° N summer insolation (W/m²)
484
482
480
g
4000
3500
3000
2500
2000
1500
1000
500
0
Age (cal yr BP)

835