**Response to editor's and reviewers' comments and suggestions**

Dear Dr. Denis-Didier Rousseau,

Thank you for the comments and constructive suggestions from the referees regarding our manuscript "A chironomid-based record of temperature variability during the past 4000 years in northern China and its possible societal implications" (ID: cp-2017-126). We find these comments and suggestions very helpful, and have carefully considered them in our revision. The revised manuscript includes the following points:

1) We have corrected all the biases in the statement, analysis and interpretation, as recommended by the referees.

2) We have corrected all the technical mistakes.

3) All the revisions are marked in red in the revised manuscript. We respond to the comments following their questions below (responses are marked in blue).

Sincerely yours,

Haipeng Wang and Jianhui Chen (on behalf of all authors)

## Point-to-Point responses to the referees' comments:

**Referee #1:**

Principal Strengths: This is a very well-written paper, including an especially interesting analysis of the correspondence between a chironomid record and Chinese written history.

Principal Weaknesses: For unknown reasons the authors have relied on a rather subjective indicator (% of cold water taxa) for the climate reconstruction, rather than more statistically rigorous reconstruction methods (e.g., weighted averaging). As a consequence, the conclusions are not especially convincing and are open to criticism. I recommend that the analysis be repeated using these more robust techniques.

**Response:** Many thanks. We have carefully considered these constructive suggestions. Statistically rigorous reconstruction methods are undoubtedly efficient techniques for reconstructing temperature change. We have tried to reconstruct the temperature change using a high quality modern calibration set. However, currently there is no suitable training set for chironomid-based temperature reconstruction in northern China. The paleoenvironmental application of chironomid analysis is relatively recent in China, and only one chironomid-based modern calibration set for temperature reconstruction was obtained from the southeastern Tibetan Plateau (*E.L. Zhang et al., 2017a and 2017b*). Our chironomid record is from northern China and consists of many different species from the Tibetan Plateau calibration set. The only training set near Gonghai Lake indicates that the chironomid assemblages in this region mainly respond to precipitation variability through changes in water depth (*H. P. Wang et al., 2016*). Fortunately, as we showed in the manuscript, there are several temperature indicator species in our fossil midge record. Furthermore, modern process research using the calibration set near Gonghai Lake suggested that all these indicator-species have significant temperature implications. The indicator-species approach, as one of the basic approaches to reconstructing past climate from paleoecological data, is regarded as the oldest and most commonly used method (*Birks et al., 2010*). The biggest strength of this approach is simplicity and unambiguity. Therefore, we selected it to assess the past temperature changes. In addition, the consistency between our reconstruction and documentary and stalagmite-based reconstructions provides further validation.

*Birks, H.J.B., Heiri, O., Seppä, H., and Bjune, A.E.: Strengths and Weaknesses of Quantitative Climate*

*Reconstructions Based on Late-Quaternary Biological Proxies, Open Ecology Journal, 3, 68-110, 2010.*

*Zhang, E.L., Chang, J., Cao, Y.M., Tang, H.Q., Langdon, P., Shulmeister, J., Wang, R., Yang, X.D., and Shen, J.: A chironomid-based mean July temperature inference model from the south-east margin of the Tibetan Plateau, China, Clim. Past, 13, 185-199, 2017a.*

*Zhang, E.L., Chang, J., Cao, Y.M., Su, W.W., Shulmeister, J., Tang, H.Q., Langdon, P., Yang, X.D., and Shen, J.: Holocene high-resolution quantitative summer temperature reconstruction based on subfossil chironomids from the southeast margin of the Qinghai-Tibetan Plateau, Quat. Sci. Rev., 165, 1-12, 2017b.*

*Wang, H.P., Brooks, S.J., Chen, J.H., Hu, Y., Wang, Z.L., Liu, J.B., Xu, Q.H., and Chen, F.H.: Response of chironomid assemblages to East Asian summer monsoon precipitation variability in northern China since the last deglaciation, J. Quat. Sci., 31(8), 967-982, 2016.*

Page 7: The statement that most chironomid taxa "barely survive in winter" is untrue. Many taxa thrive, and grow most rapidly in winter.

**Response:** Many thanks for this kind reminder. The statement "barely survive in winter" has been deleted (P.8, L.161).

Page 9: The statement that temperature plays "the dominant role in controlling the abundance of chironomid taxa in freshwater" is an overstatement. The dominant environmental control depends very much on circumstance. For example, salinity/osmolarity is more important than temperature in saline lake systems.

**Response:** We agree that temperature is one of the dominant environmental variables. The statement that "the dominant role in controlling the abundance of chironomid taxa in freshwater" has been revised as "a key role in controlling the abundance of chironomid taxa in freshwater" (P.9, L.190).

Page 12: I see no basis for the statement, "It is evident that the cold-preference taxa were more sensitive to temperature fluctuations and provide more detailed information about temperature variations than warm-preference taxa". The reader is left with no objective evidence to support this statement. It appears to be wholly based on the authors' bias and probably wishful thinking. It would be preferable to include plots for both warm-preference and cold-preference taxa to facilitate the reader's independent assessment. It also raises another issue – how objectively have taxa been assigned to these categories?

**Response:** We agree with the referee, and the previous statement has thus been revised (P.12-13, L.269-274). For comparison and assessment, the abundances of warm-preference and cold-preference taxa were both shown in Fig. 4. Both groups of taxa indicate an overall cooling trend since 4000 cal yr BP. However, the abundance of warm-preference taxa was much less than the cold-preference taxa and the former were even often absent during the past 2700 years (Fig. 4). To avoid the potential limitations of such presence or 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.

To assign objectively the typical taxa to the correct categories, several criteria were used to select indicator species before analyzing the chironomid assemblages in Gonghai Lake. Please see section 5.1 (P.9, L.201-203) for more details.

P. 14: The statement, "This result has rarely been observed in the previous literature, although it has been noted that chironomids often respond significantly to mean July or summer temperature", reflects the authors' strong bias. Since only a handful of climate variables, and no chemical variables (or other physical variables) were included in the analysis, the authors have forced the RDA to select one variable among a series of several very highly correlated variables. This is not an unbiased approach.

**Response:** 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*), which we should have introduced more clearly. Please see the revision in section 6.1 (P.14, L.309-311).

It was suggested that the chironomid taxa mainly responded to changes in precipitation (*H.P. Wang et al., 2016*). However, 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 in the present study (please see P.14, L.311-318, and also refer to the response to the previous comment).

*Wang, H.P., Brooks, S.J., Chen, J.H., Hu, Y., Wang, Z.L., Liu, J.B., Xu, Q.H., and Chen, F.H.: Response of chironomid assemblages to East Asian summer monsoon precipitation variability in northern China since the last deglaciation, J. Quat. Sci., 31(8), 967-982, 2016.*

P. 15: The authors' proclamation that the temperature variability "is clearly revealed by changes in the abundance of the cold-preference chironomid taxa" also reflects bias. The reader is supplied with no objective means for assessing that statement's validity

also on p. 15: Similarly, the statement that cold preference taxa "responded rapidly and sensitively to even minor temperature fluctuations" cannot be objectively supported. To conclude this would require a highly accurate, highly precise, and independent temperature record. To conclude this on the basis of the chironomid-inferred climate record is clearly circular reasoning.

**Response:** Previous statements are not precise indeed and have been revised. 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). However, the variations in the abundance of the cold-preference taxa were primarily used to investigate the temperature changes (please refer to the response to the previous comments). 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. Please refer to section 6.2 for more details (P.15-16, L.341-347).

Further along on p. 15: I have long been highly skeptical of the use of sediment organic content as any measure of lake productivity. The most organic sediments (95%) occur in bog-enclosed dystrophic systems. In contrast, the small hypereutrophic lakes of temperate grasslands have sediments with much lower (<50%) organic matter content. I strongly suspect that much of the organic matter accumulating in small, forest lakes is actually derived from the surrounding forest and has little or no correspondence with lake productivity.

**Response:** We agree with the referee's comment that the sediment organic content should be carefully considered as a measure of lake productivity. Gonghai Lake, an alpine lake, is situated on a small plateau in the northern part of the Lüliang Mountains. The C/N ratios of lake sediments, which is an indicator of the organic matter source in lake sediments (*Meyers and Ishiwatari, 1993*), show a gradually decreasing trend from 12 to 9.5 during the past 4000 years (*S.Q. Chen et al., under review*), suggesting that the authigenic fraction of the organic matter was dominant. Thus, it is reasonable to infer that most of the organic matter is of within-lake origin. Furthermore, there is no perennial run-off flowing into the lake and the materials which could be transported into the lake are limited. This statement has been added in section 6.2 (P.17, L.385-391).

*Chen, S.Q., Liu, J.B., Chen, J.H., Wang, H.P., Wang, Z.L., Rao, Z.G., Xu, Q.H., and Chen, F.H.: Evolution of integrated lake status since the last deglaciation: a high-resolution sedimentary record from Lake Gonghai, Shanxi, China, Palaeogeogr. Palaeoclimatol. Palaeoecol., under review.*

*Meyers, P.A. and Ishiwatari, R.: Lacustrine organic geochemistry—an overview of indicators of organic matter sources and diagenesis in lake sediments, Org. Geochem., 20(7), 867-900, 1993.*

Finally on p. 15: The temperature preferences of chironomids in Norway has questionable relevance to a Chinese record.

**Response:** Many thanks for this reminder. The previous statement has been revised. Given that *Stictochironomus* and *Procladius* were abundant in this stage as well as in the mid-Holocene (*H.P. Wang et al., 2016*), the environment during this stage may have been relatively warm. This is similar to a record from Norway which showed that *Stictochironomus* and *Procladius* indicate a relatively warm environment. Thus, we use the Norway record as a reference for the assessment (P.16, L.355-359).

*Wang, H.P., Brooks, S.J., Chen, J.H., Hu, Y., Wang, Z.L., Liu, J.B., Xu, Q.H., and Chen, F.H.: Response of chironomid assemblages to East Asian summer monsoon precipitation variability in northern China since the last deglaciation, J. Quat. Sci., 31(8), 967-982, 2016.*

P. 17: The statement that two reconstructions “were chosen for comparison” worries me. In response to such statements I always worry: were these records selected objectively? Was this choice biased, instead selected because these records best support the author’s narrative?

**Response:** These records were selected objectively. We added more description about the process of records selection in the revised manuscript (P.18, L.400-406). In this study, all the Holocene temperature reconstructions over China were collected for comparison. However, many of the records are problematic in that they have a large dating uncertainty, low resolution or are environmentally ambiguous. 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.

P. 18: The statement, "The foregoing demonstrates that our chironomid-based temperature reconstruction is reliable", is not supported by independent evidence. Such a statement requires very strong, independent evidence.

**Response:** We agree that the previous statement needs strong and independent evidence. Given that our results show a good consistency with other reconstructions, the previous statement has been corrected as "The foregoing demonstrates that our chironomid-based temperature reconstruction is reasonable and representative" (P19, L432).

also on p. 18: On what basis can the chronology be described as robust? This adjective likely reflects bias and overstatement.

**Response:** The previous statement "the robust chronology" has been revised as "the precise, high-resolution chronology" (P.19, L.434), and more details about the chronology have been added in section 3. The age-depth model for Gonghai Lake core GH09B (*F.H. Chen et al., 2015*) was used in in this study. Figure 2 shows the chronology for the last 4000 years. In the age-depth model of 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*).

*Bronk Ramsey, C.: Deposition models for chronological records, Quat. Sci. Rev., 27, 42-60, 2008.*

*Chen, F.H., Xu, Q.H., Chen, J.H., Birks, H.J.B., Liu, J.B., Zhang, S.R., Jin, L.Y., An, C.B., Telford, R.J., Cao, X.Y., Wang, Z.L., Zhang, X.J., Selvaraj, K., Lü, H.Y., Li, Y.C., Zheng, Z., Wang, H.P., Zhou, A.F., Dong, G.H., Zhang, J.W., Huang, X.Z., Bloemendal, J., and Rao, Z.G.: East Asian summer monsoon precipitation variability since the last deglaciation, Sci. Rep., doi: http://dx.doi.org/10.1038/srep11186, 2015.*

*Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Ramsey, C.B., Buck, C.E., Burr, G.S., Edwards, R., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., and Richards, D.A.: Intcal09 and Marine09 radiocarbon age calibration curves 0-50,000 years cal BP, Radiocarbon, 51(4), 1111-1150, 2009.*

Further on p. 19: On what objective basis can we conclude that this is "a detailed record of temperature changes", as opposed, for example, to a detailed record of noise in the temperature reconstruction?

**Response:** Thanks for this comment. The previous statement "(iv) the high-resolution record provides a detailed record of temperature changes" has been deleted.

P. 22: The statement that "Chironomids are a stenotypic and sensitive temperature proxy" does not appear to be well supported by this study. Stronger evidence can be found in earlier research by other authors.

**Response:** Many thanks for the reminder. The statement that "Chironomids are a stenotypic and sensitive temperature proxy" was found in earlier research by other authors, and it has been deleted in the revised manuscript.

Overall: This is an interesting paper, but it is marred by the author's apparent bias(es) with respect to the analysis and interpretation.

**Response:** Many thanks for your comments and suggestions. We appreciate all your efforts to improve this paper. All biases with respect to the analysis and interpretation, some of which may have resulted from our inappropriate expression, have been deleted or corrected in the revised manuscript.

Technical comments:

Throughout: Chinese surnames are less diverse than in other countries, which creates some problems when trying to match citations in the text with the reference list. To circumvent this issue, it is customary in most journals for in-text citations to include the given name initials for very common surnames (i.e., instances where two or more first authors share the same surname). See notes on edited manuscript.

**Response:** Many thanks for this suggestion. All citations with common surnames, including Chen, Liu, Wang, and Zhang, have been supplemented with first name initials. Please refer to the revised manuscript.

The authors are overly reliant on the use of undefined acronyms in the manuscript text. This detracts from the paper's readability, especially for non-specialists. Example acronyms include GDGT, YD, and STWP.

**Response:** Many thanks for the reminder. All undefined acronyms in this study, including EASM, GDGTs, STWP, MWP and LIA, have been defined in the revised manuscript when they occurred for the first time.

The figures should be numbered in the same order as cited in the text. This should be corrected. For example, Fig. 3 is cited (p. 6), before Fig. 2 (p. 8); and Fig. 6 (p. 13), before Fig. 5 (p. 17).

**Response:** Many thanks for your kind reminder. To make sure that the figures were cited in the same order in the text, **Chronology** has been moved behind **Regional setting** (P.6-7, L.130-139), and the previous statements about the modern training set in **Regional setting** have been moved to the second part of **Materials and methods** as a brief introduction of the training set (P7, L.154-157). The previous Fig. 5 and Fig. 6 have been re-ordered as Fig. 6 and Fig. 5 in the revised manuscript, respectively (P.40-41). The corresponding manuscript text has been corrected accordingly.

p. 24: Regarding Brooks et al. reference order: Papers with three or more authors should appear in the reference list after two-authored papers. Papers with three or more authors, and the same senior author, should be listed chronologically.

p. 25 & 26: Regarding J.H. Chen et al. and Heiri et al. reference order: Papers with three or more authors, and the same senior author, should be listed chronologically.

p. 27: Regarding Liu et al. reference order: Papers having senior authors who share the same surname, should be organised alphabetically, by the initials of the senior author's given name(s).

p. 30: Regarding E.L. Zhang et al. reference order: Papers with three or more authors, and the same senior author, should be listed chronologically.

**Response:** Many thanks for your kind reminder. These problems have been corrected in the revised manuscript.

Please also note the supplement to this comment:

https://www.clim-past-discuss.net/cp-2017-126/cp-2017-126-RC1-supplement.pdf

**Response:** Many thanks for the helpful notes. All mistakes have been corrected. Please refer to the revised manuscript.

**Referee #2:**

Northern China is one of the most important cradles of Chinese civilizations, which makes it an ideal region to study climate change and culture evolution. While high resolution regional rainfall records during the Holocene were reconstructed in the recent years, temperature records longer than 2000 years are scarce. This study reconstructed the temperature variability during the past 4000 years in northern China using fossil chironomid assemblages in an AMS 14C-dated sediment core from Gonghai Lake. The chronology of the record is robust, and the interpretation of the chironomid assemblages is convincing. This could deep our understanding of the Holocene climate change in this crucial region. My general comments are as follows: The authors compared the chironomid-based temperature record with pollen-based precipitation re- construction from the same core, and suggested the temperature and rainfall variations in northern China were out –of – phase during 650-900 AD and 1650 AD to present. Then, they suggested the recent decreasing rainfall and increasing temperature pattern in northern China may be due to natural variability. I am not fully convinced. As I see from Figure 6, the temperature and rainfall records are well consistent with each other before 1650 AD, if different resolutions are considered. During 650-900 AD, both temperature and rainfall shown similar pattern, like a letter "M". Although the temperature didn't decrease as much as the rainfall did, this could be due to the uncertainties of the record. Multiple factors could cause the inconsistence between the temperature and rainfall variations during the last 450 years, such as the uncertainties of both reconstructions, possible influence of human activities to pollen and chironomid during the last 450 years. For example, many temperature reconstructions show gradually warming trend from 1650 AD to present, like the records cited in Fig. 5, which is different from this reconstruction. The temperature maintained in a high level during the last 300 years in this record. Moreover, it shows a slight decreasing trend in the last 50 years, which is not true. In addition, Tan et al. (2011, CP) compared the tree ring and stalagmite reconstructed temperature records with synthesized rainfall record in northern China, and suggested a warm-humid/cool-dry pattern on centennial timescale over the last 1800 years. I think the authors should discuss the difference between the temperature reconstruction of this study and other studies in the last 300 years, or just leave it an open question.

**Response:** Many thanks. We have carefully considered your helpful comments and constructive suggestions, and have revised the manuscript accordingly (P.19-20, L.439-445).

We agree that the temperature and rainfall variations in northern China during 650-900 AD were generally consistent. The climate change pattern in the Gonghai Lake region would be the warm and humid/cool and dry pattern both on millennial- and centennial- scales, which is consistent with a previous synthesis study (*Tan et al., 2011*). The temperature reconstruction of this study in fact shows a broad consistency with other studies during the last 300 years, such as the rapid temperature increase at the end of LIA (see grey bar in Fig. 6). However, it might be difficult to discuss the temperature fluctuations in a more detailed way using a 60 a-resolution record. In addition, the weakening of the Asian summer monsoon suggested by the pollen-based precipitation reconstruction in Gonghai Lake during the last 300 years might be due to various factors, such as the possible impact of human activities. Therefore, more high-quality precipitation records are needed to further validate such a warm and dry configuration in this period.

*Tan, L.C., Cai, Y.J., An, Z.S., Yi, L., Zhang, H.W., and Qin, S.J.: Climate patterns in north central China during the last 1800 yr and their possible driving force, Climate of the Past, 7(3), 685, 2011.*

The other suggestion is that the authors should emphasize the differences of this work and the previous one (Wang et al., 2016) in the Introduction. In the previous study, the same authors used chironomid assemblages from this core to reconstruct rainfall variations. I understand they are different assemblages, but general readers will benefit from a clearer explanation. The authors mentioned it, but not enough.

**Response:** Many thanks for this suggestion. We have highlighted the major content of this study in the **Introduction,** which will help general readers to obtain a clearer picture. The biggest difference between these two studies is that the previous study indicates that the chironomid assemblages mainly respond to precipitation variability through water depth fluctuations, whereas this study focuses on using certain stenothermic taxa to reconstruct past temperature changes. The temperature record in this study has more samples and a higher resolution, and only the temperature indicator species were used. Please refer to the revised **Introduction** for more details (P.4-5, L.89-93, 100-102).

I also have some special comments:

1. If the inconsistence of temperature and rainfall variations are plausible, conclusion 3 in the

abstract should be modified. Rainfall changes could also had influenced the human society in northern China.

**Response:** The conclusion 3 in the abstract is based on the results of Pearson correlation analysis and Granger causality analysis of cold-preference taxa, reconstructed precipitation and the incidence of war. We agree that rainfall changes could also have influenced the human society in northern China as a whole. However, the relationship between climate change and societal implications in our study is limited to Shanxi Province. On such a regional scale, further work is needed to explore the influence of precipitation changes on human society.

2. Line 46: Stalagmite d$^{18}$O record from Dongge cave is not a typical EASM rainfall record, so Dykoski et al. (2005) should be removed from the reference list. The authors can replace it with Hu et al. (2008, EPSL) or Cai et al., (2010, EPSL).

**Response:** Thanks. Dykoski et al. (2005) has been deleted, and Hu et al. (2008) and Cai et al. (2010) have been added in the revised manuscript (P.3, L.47).

*Cai, Y.J., Tan, L.C., Cheng, H., An, Z.S., Edwards, R.L., Kelly, J.M., Kong, X.G., and Wang, X.F.: The variation of summer monsoon precipitation in central China since the last deglaciation, Earth Planet Sci. Lett., 29, 121-131, 2010.*

*Hu, C.Y., Henderson, G.M., Huang, J.H., Xie, S.C., Sun, Y., and R. Johnson, K.: Quantification of Holocene Asian monsoon rainfall from spatially separated cave records, Earth Planet Sci. Lett., 266(3), 221-232, 2008.*

3. Line 92-94: Tan et al. (2011, Holocene) compared the climate changes and war frequencies in northern China during the last 1860 year, and detailed discussed the impacts of regional climate changes on social evolution. This paper should be cited.

**Response:** Tan et al. (2011) has been cited in the revised manuscript (P.5, L.100). Especially, it gave us more thinking about the impacts of precipitation changes on social evolution on different spatial scales.

*Tan, L.C, Cai, Y.J., An, Z.S., Edwards, R.L., Cheng, H., Shen, C.C., and Zhang, H.W.: Centennial-to decadal-scale monsoon precipitation variability in the semi-humid region, northern China during the last 1860 years: Records from stalagmites in Huangye Cave, Holocene, 21(2), 287-296, 2011.*

4. Line 142-146: did you exclude the winter temperature in the reconstruction of TANN?

**Response:** We did not exclude winter temperature in the reconstruction of TANN. We just did not consider the winter temperature variable in the RDA (Fig. 3b), given the fact that the lake surface freezes in winter (see below photo taken in Jan 2009) which will definitely disrupt the good relationship between water temperature and air temperature (P.8, L161-164). Furthermore, the winter season is not the growing season for midges (*Armitage et al., 1995)*.

*Armitage, P.D., Cranston, P.S., and Pinder, L.C.V. (Eds): The Chironomidae. Biology and ecology of non-biting midges,. Chapman and Hall, London, 1995.*

5. Line 186-188: seems inconsistent with line 143-146.

**Response:** We have revised the previous statement (P.8, L161-164). Please refer to the response to the above comment.

6. Better to combine section 5.3 with 6.2 and section 5.4 with 6.4.

**Response:** Many thanks for this suggestion. It is a hard decision to separate them. To combine section 5.3 with 6.2 and section 5.4 with 6.4 could simplify the paper and make it easier to read. However, our main concern is that sections 5.3 and 5.4 are the results of the study which are objective, and sections 6.2 and 6.4 are the corresponding discussion. If they are combined, readers might find it difficult to assess the results independently.

7. It's better to use bars to indicate different periods in figure 5 and figure 6. It's hard to compare in the present version.

**Response:** The fact that the bars in Fig. 5 and Fig. 6 are difficult to distinguish may be due to their very light color (and the low resolution of the image). We have darkened the color of the bars (please refer to Fig. 5 and Fig. 6 in the revised manuscript).

8. Line 382: 1150-1350 cal yr BP should be MWP, and 650-950 cal yr BP should be STWP.

**Response:** 1150-1350 cal yr BP, which equals 600-800 AD, should be STWP. 650-950 cal yr BP, which equals 1000-1300 AD, should be MWP. We did not use "AD" here because many other records for comparison used "cal yr BP".

9. Line 453: as I see from figure 6, the rainfall also decreased during 760-230 BC and 260-600 AD.

**Response:** Many thanks for this comment. We agree that the rainfall also decreased during 760-230 BC (2180-2710 cal yr BP) and 260-600 AD (1350-1690 cal yr BP). The previous statement is not precise and we have corrected it as "The incidence of war was especially high during 900-1050 AD (900-1050 cal yr BP) and 1300-1650 AD (300-650 cal yr BP) when both temperature and precipitation were lower; it was higher at these times than during the periods of 760-230 BC (2180-2710 cal yr BP) and 260-600 AD (1350-1690 cal yr BP) when the decrease in temperature was more severe than that of precipitation" (P.21, L.477-478).

# 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.

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**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).

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**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 (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 stratigraphicallyconstrained 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).

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**Figure 3**

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## 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.

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**Figure 4**

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## 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.

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**Figure 5**

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**Table 1**

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**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., under review) 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.

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**Figure 6**

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### 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 during cold periods, suggesting that population size was significantly influenced by climate change.

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 $1219.8\times10^6$ to $1951.3\times10^6$ kg, a reduction of almost 50% compared to the yield of ~1580 ($2439.1\times10^6$ 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 events, 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.

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

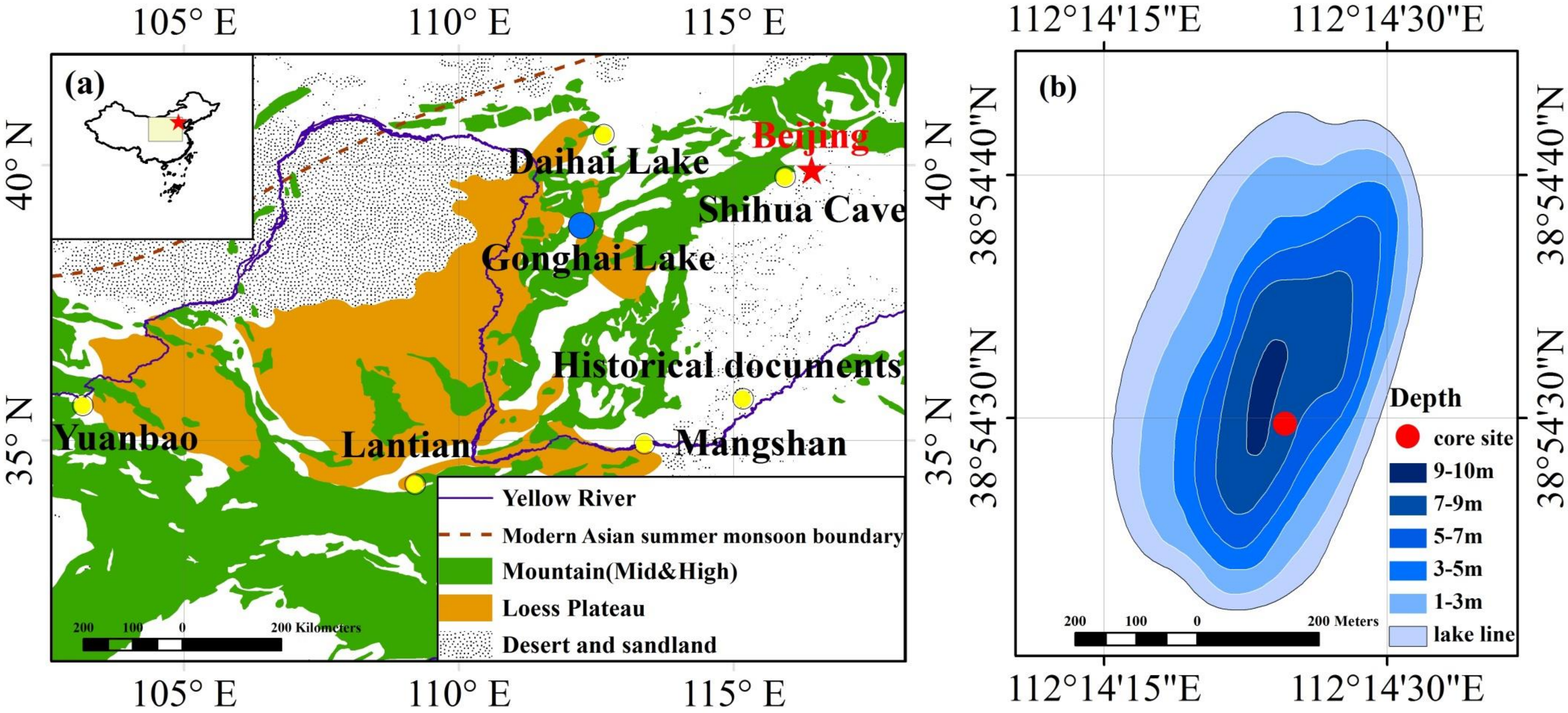
**Figure 3** Information about the modern calibration data set obtained from the Gonghai Lake area. (a) Location of modern surface samples (white dots); (b) RDA bi-plot of modern chironomid assemblages and TANN, summer Tem, June Tem, July Tem and August Tem; and (c) relative abundance of modern chironomid 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 abrupt temperature decreases.

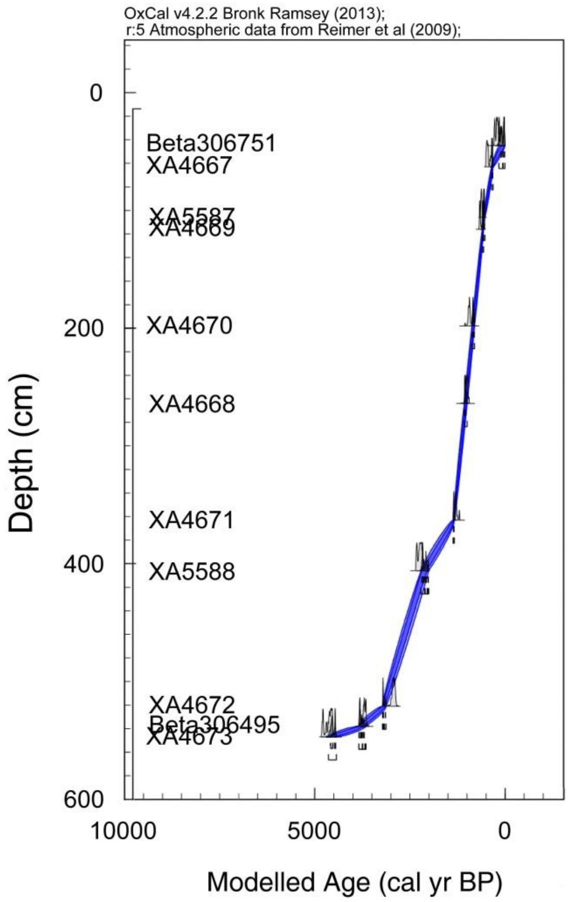
**Figure 6** Comparison of (a) cold-preference taxa percentages in Gonghai Lake with intraregional temperature records during the past 4000 years, including (b) reconstructed temperature based on stalagmite layer thickness in Shihua Cave (Tan et al., 2003), (c) winter half-year temperature anomalies 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). 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 periods.

**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
0
200
400
600
Depth (cm)
10000
5000
0
Modelled Age (cal yr BP)

**Fig. 3**

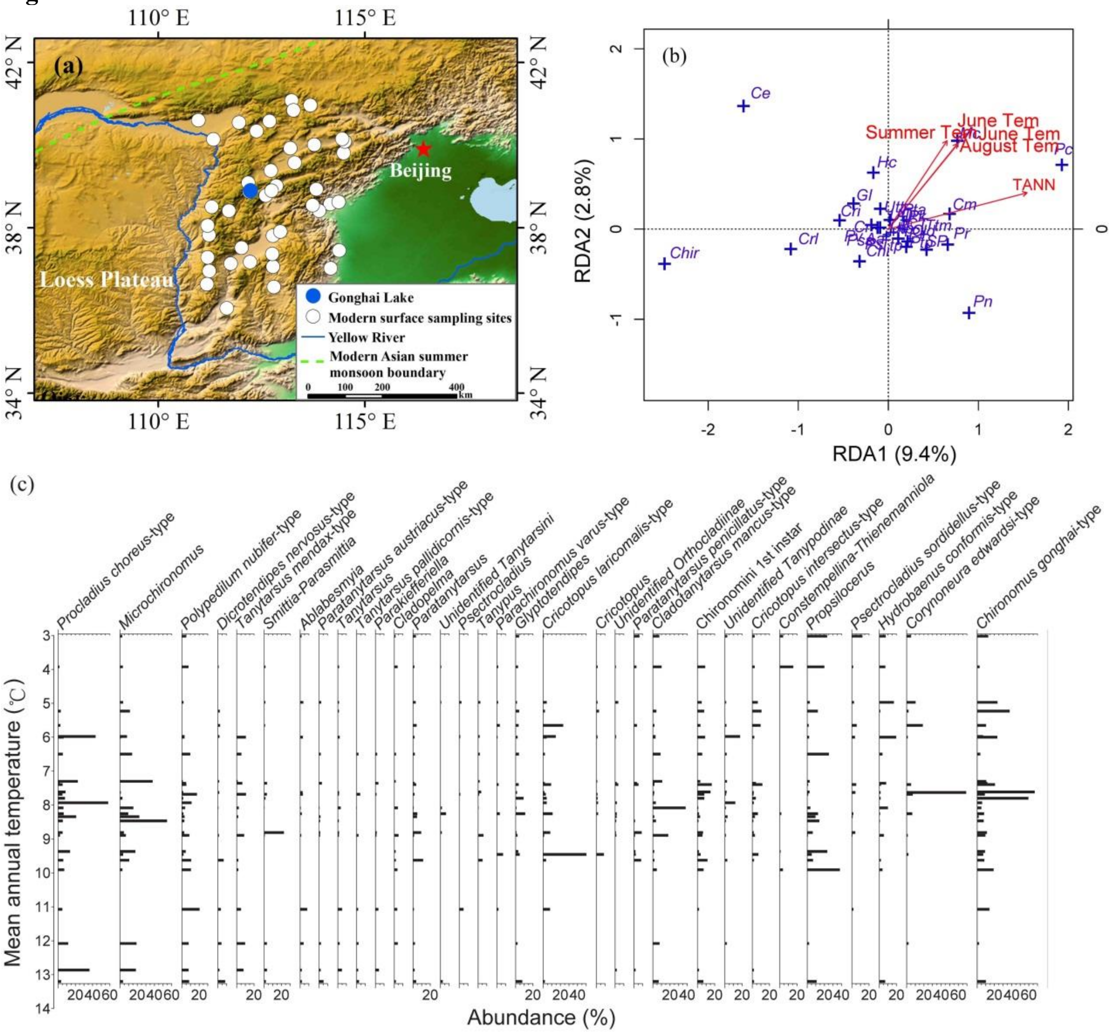

(a)
110° E
115° E
42° N
38° N
34° N
Beijing
Loess Plateau
Gonghai Lake
Modern surface sampling sites
Yellow River
Modern Asian summer monsoon boundary
(b)
RDA1 (9.4%)
RDA2 (2.8%)
June Tem
Summer Tem
July Tem
August Tem
TANN
(c)
Mean annual temperature (℃)
Abundance (%)
Procladius choreus-type
Microchironomus
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

**Fig. 4**

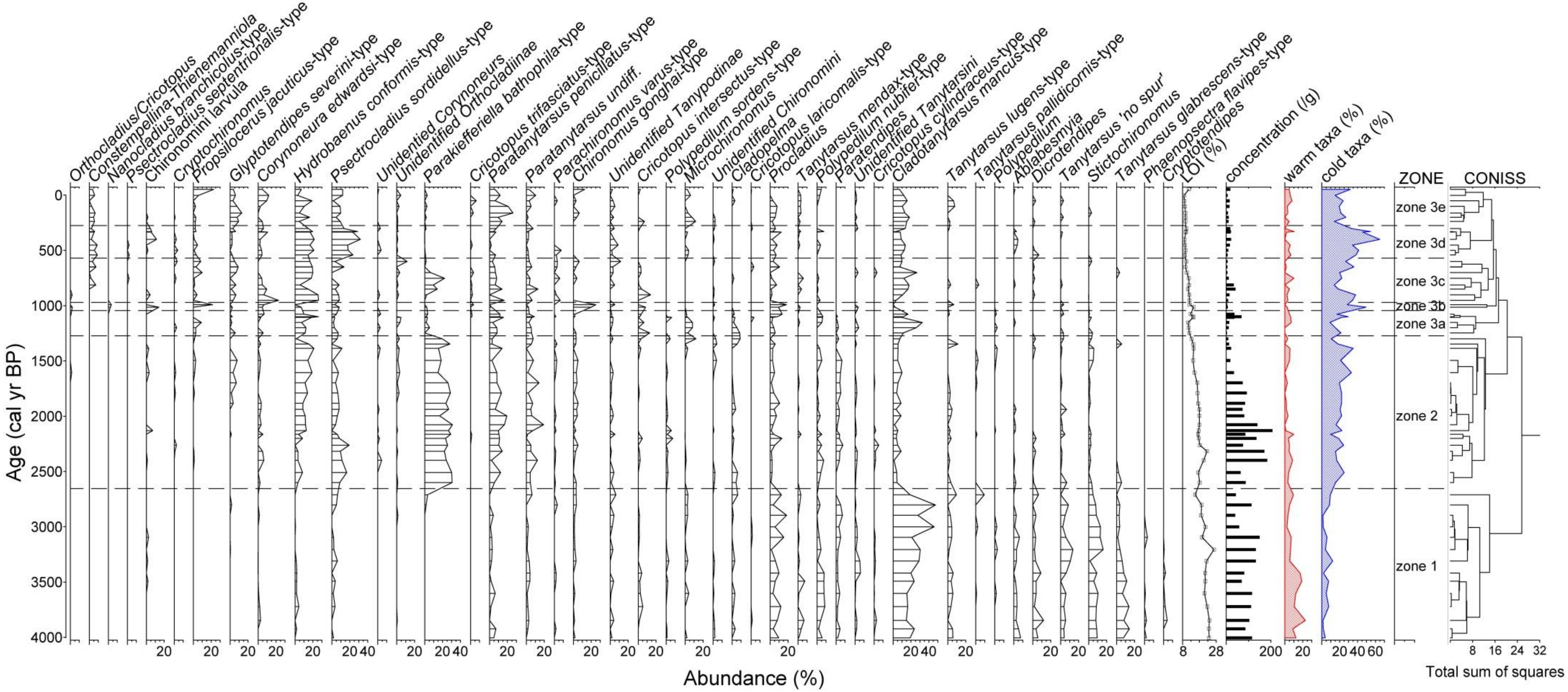
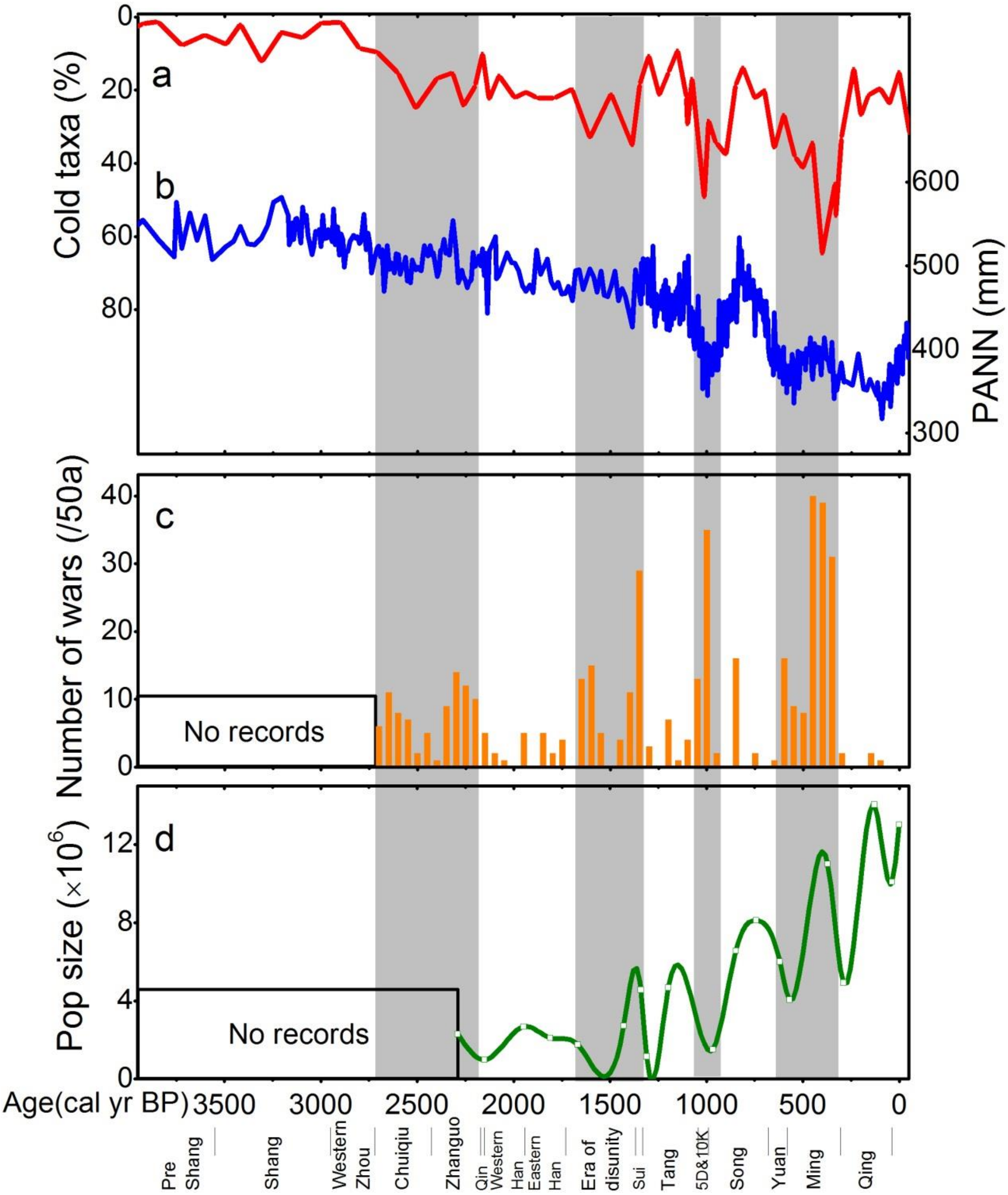
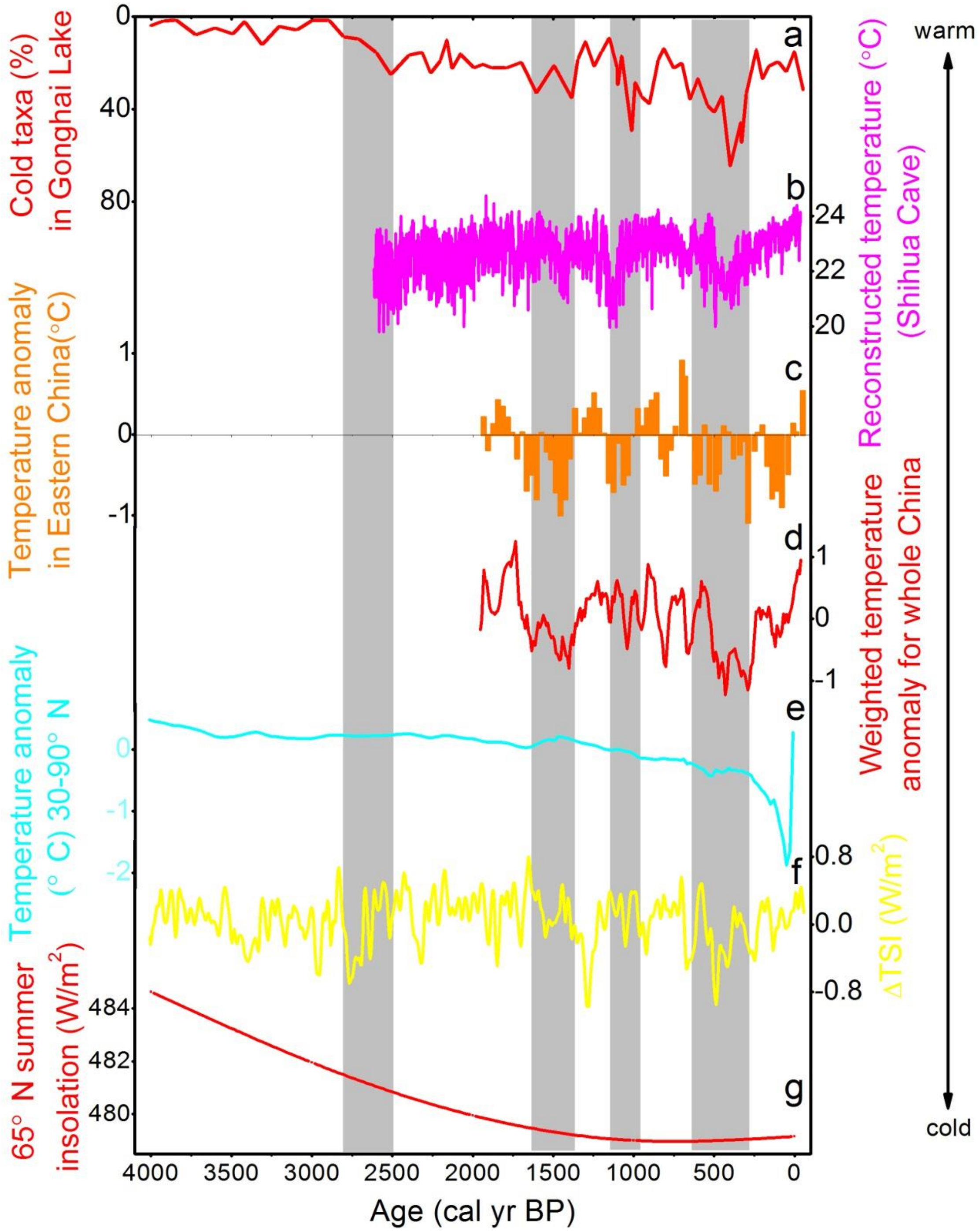

Orthocladius/Cricotopus
Constempellina-Thienemanniola
Nanocladius branchicolus-type
Psectrocladius septentrionalis-type
Chironomini larvula
Cryptochironomus
Propsilocerus jacuticus-type
Glyptotendipes severini-type
Corynoneura edwardsi-type
Hydrobaenus conformis-type
Psectrocladius sordidellus-type
Unidentied 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)
0
500
1000
1500
2000
2500
3000
3500
4000
Abundance (%)
Total sum of squares
8
16
24
32
20
40
28
200
60

**Fig. 5**



Cold taxa (%)
0
20
40
60
80
a
b
600
500
400
300
PANN (mm)
Number of wars (/50a)
40
30
20
10
0
c
No records
Pop size (×10^6)
12
8
4
0
d
No records
Age(cal yr BP) 3500 3000 2500 2000 1500 1000 500 0
Pre Shang
Shang
Western Zhou
Chuiqiu
Zhanguo
Qin
Western Han
Eastern Han
Era of disunity
Sui
Tang
5D&10K
Song
Yuan
Ming
Qing

824 **Fig. 6**


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

825