Response to the comments

Editor

Both reviewers comment on the need for additional terrestrial records of past climate, and the potential value that records like this could have for improving our understanding of climate changes in this region.

Both reviewers have provided a suite of constructive comments for improving the manuscript (including the annotations by Reviewer 1). Some of these are relatively minor e.g. typos, or change of phrasing. However, the reviewers raise important concerns which limit acceptance of the results and interpretations being presented by the authors.

Both reviewers comment on the need to significantly increase the detail of the descriptions of the proxies that are being applied. The authors currently have a brief introduction, and then later (section 4.1) provide the overview of the proxy interpretations. The reviewers sought to move section 4.1 into the introduction, which the authors note they can do in a revised version. However, neither reviewer was satisfied by the depth of discussion about the proxies even in section 4.1. Reviewer 2 gives a large number of references where the authors could both explain the rationale of the approach, but also make much more detailed and nuanced interpretations of the data. The combined comments of the reviewers indicate that work is required to justify both the approach taken and the results generated. Furthermore, the existing discussion of the proxy data and its interpretations is not well connected to the modern lake system: both reviewers comment on the need to better understand how the lake works today, and what environmental factors might be at play which could impact the GDGTs (e.g. pH, salinity... as well as temperature).

Finally, both reviewers comment that although a presentation of other regional climate records is made in the final section of the Discussion, this is not discussed well: the causes of similarities and differences are not explained sufficiently to the reviewers. The manuscript provides an overview of patterns of change but does not dig into evaluating the causes / mechanisms / limitations of the data sets.

The Author Comments in reply to the Reviewers suggest that some of these issues may be addressed. The minor comments of both reviewers are indicated to be ‘modified’ and in many instances these will be easily achieved.

However, it is difficult from the responses at present to be clear that all changes can be easily included into a revised manuscript, and especially those of a substantive nature e.g. both reviewers ask for increased detail in the controls over GDGT production in lakes, and more detail about this lake. But the replies from the authors to these comments are very brief, implying that they may not consider adding the level of detail the reviewers would like to see. For example, R1 comments 20 and 21, and R2 comments 3, 4 and 15 (among others), seek detail and discussion but the current replies don’t provide additional justification for why these interpretations were made. Some of the author replies are “that’s not the same in this lake” when comparing to the literature cited by the reviewers, but in the absence of detail about this lake and it’s properties these statements are not fully justified. There will be some differences between systems, but that is all the more reason to detail the steps the authors took to make their interpretations based on other literature and the local factors.

I am prepared to review an updated version of this manuscript, where the authors show that they have made substantive edits and additions according to those requested by the reviewers. Both reviewers have provided very constructive comments about the complexities of the proxies, the need for these to be better detailed, and the need for the interpretations to be better explained as a result. I expect that the revised Introduction section (or a new section 2) provides a review of the key proxies, their interpretations and their limitations. There should also be increased detail about the modern properties of this lake, and how this might affect those same proxies. This ought then to link with why they might expect, for example, cren/cren’ to record lake level changes, and how that could link to e.g. hydrological change in the region. The authors should carefully consider the substantive comments about content provided by both reviewers, and increase the depth of information they provide as well as their critical evaluation of the literature.

Once the proxy-based changes have been completed, the authors also then need to carefully incorporate the comments about how they are linking their data to other records from the region. I agree with the reviewers that at present this lacks critical evaluation of the processes which are being recorded, and how/why there are agreements and disagreements between the records. But it remains difficult to assess this component of the manuscript at present where there remain many questions about how the authors reached the interpretations they have made of their data in the preceding sections.

Finally, the authors should note that the similarity report run as part of the submission process indicated that sections of the Methods part of the manuscript are also found, with only minor changes, from the same authors in a paper published in Quaternary Science Reviews in 2019. The authors should try to reduce this duplication in any revised submission.

Response: *We have revised the manuscript according the comments from both reviewers. Firstly, we reorganized the manuscript with moving the section 4.1 to the introduction and adding some new references to make the interpretations of the proxies more clear. Secondly, the concentrations of cren' in surface sediments are generally at the detection limit, resulting in* TEX_{86} *values that could not be calculated and compared to the modern values and connected to the modern lake system. Thirdly, we have focused on the temperature records from the Indian monsoon region, and paid more attention to differences between these records and possible forcings of these differences. Finally, we revised the sections of the Methods part of the manuscript and reduced the similarity.*

Referee #1

1) The assessment of GDGT as paleoclimate and paleohydrology proxy lack of

in-depth discussion on the complex interpretations of the lipids. For instance, the paper does not address the fact that it is well known that GDGT composition is highly affected by a variety of environmental factors including air and water temperature, pH, salinity etc., which can complicate the interpretation of the proxy used (e.g. Pearson et al., 2008, Wang et al., 2013). The paper also attempts to present and discuss the Lake Chenghai record in the context of the larger Indian Summer Monsoon region (including records from China and Japan). However, there is a substantial lack of detailed comparison between the Lake Chenghai record and other records shown in Fig. 5. Specifically, there is almost no mention of the differences between records and there is little discussion on the causes of the climatic variation in the studied lake and what might cause the regional differences observed in the records presented in Fig. 5. Therefore, I suggest that the authors should provide more discussion on the use of GDGTs as proxy and how they perform in relation to other records (agree/disagree).

Response: *The pH and salinity are reported to influence the isoGDGT composition in the saline lakes, however, the salinity in Lake Chenghai is relatively low at present. In addition, we conclude that it was not a saline lake during the H1 cold event when the climate was driest during the past 16 ka based on the mineral composition of the sediments (Sun et al., 2019). Thus we focus on the influences of lake level and air temperature in this study (Section 4.2 and 4.3). We also not only compare the reconstructed temperatures with those from the Indian monsoon region, with the records from East Asian monsoon region (East China and Japan where was not influenced by Indian Summer monsoon) being deleted in the revised text. In total, the magnitudes of temperature variations are consistent with these other studies considering the RMSEs of the calibrations (L402-437 in the revised manuscript without markers).*

Sun, W., Zhang, E., Shulmeister, J., Bird, M.I., Chang, J., Shen, J.: Abrupt changes in Indian summer monsoon strength during the last deglaciation and early Holocene based on stable isotope evidence from Lake Chenghai, southwest China. Quaternary.

Sci. Rev. 218, 1-9, DOI: 10.1016/j.quascirev.2019.06.006, 2019.

2) The authors mentioned in the method section that both isoprenoid and branched GDGTs were extracted and analysed. However, they use brGDGTs only to calculate BIT index but do not use any of the numerous brGDGT based temperature proxy (e.g. MBT/CBT, MBT'/CBT). Instead only isoGDGT derived TEX_{86} was adopted for temperature reconstruction. However, TEX_{86} was only applicable to approximately half of the core (57 out of 102 samples) due to the high contribution of soil derived isoGDGTs. As stated by the authors, there is scarcity of terrestrial temperature records from the studies region, therefore I strongly suggest that brGDGTs-based paleothermometers should be calculated and applied downcore in Lake Chenghai to increase the resolution and the knowledge of air and water temperature changes in the region. Finally, GDGT-based calibrations (in this case TEX_{86} inferred lake surface temp.) should not be "blindly" applied for downcore climate reconstruction. I strongly suggest that correlation analysis between iso (and eventually brGDGT) based proxies and modern water temperature and air temperature should be performed to test the validity of using GDGT for paleoclimate reconstruction.

Response: *Thanks. Firstly, branched GDGTs have been successfully used to reconstruct temperature in monsoonal Asia, such as for records derived from Lake Tengchongqinghai, Lake Tiancai and Lake Ximenglongtan in southwest China. However, the areas of these lakes are relatively small and the branched GDGTs are dominantly by contributions from the catchment soil. In contrast, Lake Chenghai is much larger, and hence in-situ production of branched GDGTs in Lake Chenghai cannot be fully excluded. We did attempt to reconstruct a temperature record based on branched GDGTs using the calibrations from both African lakes and temperate China, but large discrepancies were evident between the temperature calculated from modern samples and observed modern temperature. Here we do not believe the branched GDGTs yield meaningful information in this study. Secondly, the concentrations of cren' in surface sediments are generally at the detection limit, resulting in* TEX_{86}

values that could not be calculated and compared to the modern values.

3) I suggest that the introduction and the discussion should be throughout modified and potentially revised. In the introduction, there is not enough background on the proxies used (e.g. the producers, the environmental factors affecting TEX86, %cren, cren'/cren and GDGT-0/cren ratios), and there should be more clarification on why it is important to reconstruct lake level changes in the context of modern climate and future predictions. In the discussion, from line 220 to 254 the authors provide a literature review on the proxies used. This section should not be in the discussion, but rather be part of the introduction. Additionally, sections 4.2 and 4.3 are too descriptive and are not well connected between each other. As most of section 4.1 should be in the introduction I suggest to revise the discussion focusing on the a) interpretation (not description) of the proxies used, b) contextualise the climate and hydrological changes within the region and discuss in detail the causes of the changes and the implications for future scenarios, c) evaluate the proxies used for Lake Chenghai as mentioned in point 1 above.

Response: *We modified the structure of the manuscript in line with the suggestions of the reviewer, and moved section 4.1 to the introduction.*

4) I strongly advise for this manuscript to be revised by either a professional translator or a native English speaker as there are large portions of the text which should be rephrased as they are difficult to follow/read. Additionally, I have noticed grammar and stylistic mistakes which I have tried to amend as much as possible. I have also provided suggestions on how to rephrase some of the sentences.

Response: *Thanks. The manuscript has been proof read by both Shulmeister and Bird, who are both native English speakers. We also have corrected the grammar and stylistic issues identified by the reviewer in the revised version of the manuscript.*

5) In the introduction I think you should add a figure with the structure of iso and brGDGTs.

Response: *The structures of isoGDGTs are shown in the supplementary figure and branched GDGTs were not discussed in the manuscript further, hence we have not added an additional figure into the text.*

6) Lines 61 to 74: in this section you need to explain specifically why it is important to reconstruct lake level changes. What do these changes tell us about the hydrological budget?

Response: *Lake level may reflect the precipitation in the past, however, temperature also has significant effects on evaporation and regional hydrological cycle. In the revised manuscript, we focus on the reconstruction of temperature due to there remains a lack of quantitative reconstructions of terrestrial temperature from the Indian summer monsoon region (L68-72).*

7) Line 80: You should be more specific and list the producers. We know for example the phyla that produce isoGDGTs (e.g. Euryarchaeota)

Response: *Modified.*

8) Line 85 to 98: This is not enough introduction to TEX_{86} nor %cren, additionally there is no mention of cren'/cren ratio. I'd suggest you move section from line 220 to 254 here (see point 3 above)

Response: *Changed as requested (L109-118)).*

9) Line 129 – 130: you should make clearer that the chronology for this lake has already been published in Sun at el. 2019

Response: *Yes, the chronology has been published, the text has been modified to better reflect this fact (L187-195).*

10) Lines 145-146: This is an unusual way for extracting lipids, can you add a reference?

Response: *The method follows Feng et al. (2019) (L201-202), which has been added to the revised text.*

Feng, X., Zhao, C., D'Andrea, W.J., Liang, J., Zhou, A., Shen, J.: Temperature fluctuations during the Common Era in subtropical southwestern China inferred from brGDGTs in a remote alpine lake. Earth. Planet. Sc. Lett. 510, 26-36, DOI: 10.1016/j.epsl.2018.12.028, 2019.

11) Line 169: This is the first time you mention brGDGTs. They should be briefly introduced in the introduction section alongside the BIT.

Response: *The index of BIT was deleted.*

12) Line 202: You should report r not r2 (as r is the correlation coefficient)

Response: *Modified (L260).*

13) Lines 220 to 254: this section is a literature review and contextualizes the use and potential drawbacks of GDGTs and the GDGT-based proxy. Therefore, it should be rewritten into the introduction section.

Response: *As noted in the main points this text has been moved to the introduction*

(L84-146).

14) Line 257: which modern processes? what do you mean by that exactly?

Response: *The "modern processes" is deleted.*

15) Lines 262 - 286: Here you are simply presenting the results of cren/cren' and GDGT-0/cren ratios with a bit of contextualisation within the literature. This should be better explained within the context of climate and hydrological changes.

Response: *Modified as suggested (L103-106, 119-129).*

16) Line 293: "Deep lake conditions" Such as? Can you list some of the conditions affecting the Thaumarchaeota growth?

Response: *This sentence was deleted in the revised manuscript.*

17) Line 311/ Fig. 4 : Here you mention diatom record but in Fig. 4 you only plot the grain-size record. Could you add the acidophilous record in fig 4?

Response: *We have added the diatom record to the revised figure.*

18) Line 320: You should add what proxy you are talking about. E.g. "Lake levels inferred from %cren do not show a lowstand during the YD, which is generally recognised as a period of low rainfall due to the weakening of the ISM"

Response: *Modified as suggested.*

19) Line 320-321: add the start and end dates for the YD

Response: *Modified as suggested (L351-354).*

20) Lines 327-330: You should discuss this more. Is it just due to the sensitivity or do other environmental factor affect the proxies that you are presenting? IsoGDGTs including cren and cren' are affected by air and water temperature, pH etc. which can complicate the interpretation of the proxy used. Discuss this further.

Response: *We mainly attribute this difference to the source change of isoGDGTs, such as soil erosion and deep-dwelling Thaumarchaeota group 1.1b (L358-367).*

21) Lines 336-339: So how does this impact your interpretation of the %cren record?

Response: *This is the secondary reason for the lake-level reconstruction, the source change of isoGDGTs is the primary explanation (L358-367).*

22) Lines 340-343: This needs to be further discussed and more details are needed. For instance, cren'/cren record during H1 event appears to be more variable than what you say with a substantial trough at approx. 15.5 cal ka BP, suggesting a shift in archaea community. This change occurs alongside changes in BIT and GDGT-0/cren and grain size. Expand on this.

Response: *We interpret the secondary peak of %cren centered at 15.2 cal ka BP as a centennial monsoon event, which corresponded to the strengthened ISM recorded by speleothem records from Dongge Cave in southwest China. In addition, we suggest that %cren values may be more sensitive to lake-level change when the lake was at a lowstand (L368-378).*

23) Section 4.3 from line 344: This section does not discuss the causes of the warming during the early Holocene. You are simply comparing the Lake Chenghai record with

other record from the region without offering any explanation on the reason of climate warming. Additionally, you don't highlight any differences between the records (and therefore the region) and what might the causes of the regional climate differences. There is a very brief discussion offered in lines 398-402 but this is not enough.

Response: *We expand this to a paragraph to add this explanation (L438-454).*

Referee #2

1) Proxies. The authors use a suite of proxies based on GDGTs, such as TEX_{86} for temperature, the BIT index, %cren, cren'/cren, GDGT-0/cren. However, the proxies and the mechanisms underlying the proxies are only poorly introduced and explained, if at all (e.g. cren'/cren results are presented (L199) but the ratio is not mentioned in the introduction). Also the interpretation of the proxy data and the assessment of the applicability of the TEX_{86} proxy, and thus the reliability of the produced temperature record, is very marginal and should be improved.

Response: *We have integrated the section 4.1 to the introduction and the underlying mechanisms about isoGDGT-based proxies are introduced more detailed. This is the same point as referee 1.*

2) Structure: This comment may already resolve part of my comment on the proxies, as some of the explanation is presented in the discussion rather than in the introduction. Actually, most of section 4.1 consists of a literature overview of the proxies. This should be moved to the introduction. Instead, use the discussion to actually interpret and discuss your own data. This is also true for the other sections of the discussion.

Response: *We have integrated the section 4.1 to the introduction.*

3) Lake Chenghai: In order to interpret the GDGT data it is important to provide some more details on the modern lake. Please add basic information on the lake type (i.e. mixing regime), nutrient status (ammonia!), oxygen content, etc, and possible links to climate (e.g. is mixing related to windiness or precipitation, or: : :?).

Response: *More detail on the lake has been included, for example, the nutrient and thermal stratification (L168-174 in the revised manuscript without markers). Lake Chenghai is a seasonal mixed lake in summer and a eutrophic lake at present.*

4) Lake level reconstruction: The authors use %cren and cren'/cren to reconstruct the lake level over time, for which they assume that crenarchaeol will be produced more during lake highstands, and less during lowstands. This is in turn linked to mixing of the lake, where more mixing is related to oxic conditions, supposedly occurring during low lake levels. In order to go with this interpretation it is crucial to understand the production of crenarchaeol in lakes, for which you need to discuss the exact niche of crenarchaeol-producing Thaumarchaeota in the lake water column. Several studies have shown that they primarily occur just above the oxycline (as correctly reported in L238). This means that the position and the stability of this oxycline is very important for the amount of crenarchaeol that is produced in a lake. Hence my request for more information on the mixing regime of Lake Chenghai. For example, Buckles et al. (2013, Environmental Microbiology) hypothesize that crenarchaeol is mainly produced during years. Check Loomis et al., 2014 GCA, Weber et al., 2015 GCA, Weber et al., 2018 PNAS, Colcord et al 2015 Org geochem, Colcord et al., 2017 Org geochem , Buckles et al., 2014 GCA. The BIT index is basically an indication of crenarchaeol and/or brGDGT production in the lake. As BIT is a ratio, both cren and brGDGTs can drive changes in BIT, which can only be assessed with absolute abundances of the GDGTs. Without these data any changes in BIT should be interpreted with care. Since BIT and GDGT-0/cren practically show the same trends in Lake Chenghai (Fig. 3) it can be assumed that these changes are caused by changes in cren rather than brGDGTs and GDGT-0. So instead of enhanced soil input, the

absence of crenarchaeol production then explains a high BIT (and high GDGT-0/cren) in the interval from 6-14ka. It is up to the authors to find an explanation for the limited/disturbed niche of the Thaumarchaeota in the water column (outcompeted? Ammonia depletion?). Also, if BIT is so high (>0.5) that application of the TEX_{86} is limited, then why did the authors not attempt to use brGDGT-based paleothermometry?

Response: *Compared with the permanently stratified Lake Challa, Lake Chenghai is a seasonal stratified lake and the nutrient load mainly depends on the terrestrial organic matter input, not mixing and vertical transport from bottom water. This is consistent with the results from Lake Qinghai in northwest China (L320-333). In addition, we also suggest that part of the brGDGTs might be derived from both soil and the in suit in the water column, and it would be difficult, if not impossible, to discriminate between the sources. Thus, we did not consider the BIT values further in filtering the* TEX_{86} *values for lake surface temperature reconstruction. Consequently, the temperature series expanded to 74 data points.*

5) L82: take more time to introduce the proxies here and to explain their underlying mechanism(s).

Response: *Modified. Thaumarchaeota have a physiological mechanism to increase the weighted average number of cyclopentane rings in their membrane lipids as growth temperature increases. We have included more detail on underlying theory about the application of isoGDGT-based proxies in the revised manuscript (L107-109).*

6) L89: index is not reliable in small lakes – mention why not?

Response: *Modified. The index may not be a reliable proxy for past temperature in small lakes due to substantial amounts of soil and/or methanogenic archaea* *isoGDGTs identified in the same lacustrine sediment and variability in the depth of iGDGT production in aquatic ecosystem (L114-118). This is now made clear in the revised text.*

7) L91: explain this better. Also elaborate on the link between lake level and depth of the oxycline.

Response: *The discussion of the influences of water depth and nutrient are expanded in the text (L119-146).*

8) L141: was any standard added for GDGT quantification?

Response: *There was no standard added for GDGT quantification.*

9) L180: Castaneda and Schouten 2015 is not correctly listed in the reference list. Please check.

Response: *Checked. Both Castaneda and Schouten 2011 and 2015 were listed in the references.*

10) L189: it would make sense to start with presenting the age model. If these are not your results (it seems like they are already published?), then add a brief description to the methods. This also allows you to already indicate the position of H1 and the YD in your record.

Response: *Yes, the results are published and the position of the H1 and YD event are clear. This is clarified in the text.*

11) L199: This is the first mention of the crenarchaeol'/crenarchaeol ratio. Include

this in the introduction (if you want to use it)!

Response: *The construction and meaning of this ratio has been added to the introduction in the revised version.*

12) L204: GDGT-0/cren ratios >2 generally indicate anoxic bottom water conditions. Is this also visible in the lake core? Is the interval with values >2 also laminated? Such an easily obtained visual aspect of the core can be used to confirm/strengthen your interpretation of the GDGT record.

Response: *GDGT-0 is a common lipid and derived from a variety of archaea, not just limited to methanogenesis, thus GDGT-0/cren >2 may not indicate anoxic bottom water conditions in Lake Chenghai either during the H1 dry event or the present.*

13) L219: the title of this section suggests a discussion of all proxy records, however, it mainly comprises a literature review that focuses on aspects that may or may not affect the applicability of the TEX_{86} proxy. Hence, content does not fit the title. All proxy description should go in the introduction, and this section should focus on the data presented here. Interpretation of the data may be more thorough and critical. As illustrated in my main comments there may be multiple explanations for certain trends in the proxy records (e.g. BIT, influence of mixing regime on cren production) that need to be evaluated here.

Response: *Thanks, we modified this section to trace the provenance of isoGDGTs and the previous contents were integrated into the introduction.*

14) L221: instead of citing the GDGT review by Schouten et al., 2013, refer to the original paper instead, giving credit to the right people.

Response: *Blaga et al. (2009) and Powers et al. (2010) were added as the references.*

15) L241-248: pay special attention to linking %cren to high- and low lake levels, as there are multiple ways to explain cren production in lakes. Think about the niche of the Thaumarchaeota and the mixing regime of the lake, and how this is related to climate.

Response: *Mixing regime and nutrient status are considered to explain the differences in the responses of Lake Challa and Lake Chenghai to lake-level change.*

16) L253: as outlined above, the BIT index can no longer be linked to soil input. There is too much evidence for a primarily aquatic source of brGDGTs in lakes. See suggested references in main comments. Also note that brGDGT production in lakes takes place in the anoxic part of the lake. Hence, high BIT could be coupled to stratified water column conditions and reduced mixing. Check if this coincides with the concentrations of GDGT-0 and potential lamination of the core.

Response: *The sources of branched GDGTs in Lake Chenghai have not been identified at present, but the high BIT values did not indicate anoxic conditions during the H1event when compared with other records from this region.*

17) L267: check the cren'/cren ratios and associated DNA analysis in the water column of Lake Malawi (Kumar et al., 2019, Org Gechem). They reach values up to 0.12 without soil input.

Response: *The results show that the deep-dwelling Thaumarchaeota is also likely a Group I.1b population, similar to the soil source. However, the total production of isoGDGTs by this group appears to be much lower than the surface-dwelling Thaumarchaeota. This is now mentioned.*

18) L283-286: see earlier comment on the contradiction between high GDGT-0/cren ratios implying anoxic bottom waters and reduced mixing and low %cren supposedly indicating more mixing due to a lowstand.

Response: *Same response as earlier. GDGT-0 is a common lipid and derived from a variety of archaea, not limited to methanogenesis, thus GDGT-0/cren >2 may not indicate anoxic bottom water conditions in Lake Chenghai during either the H1 dry event or at present..*

19) L327: different responses in GDGTs between H1 and YD, where similar climatic conditions are expected, should be better explained. Also take into account that not only temperature changed during the YD, but that also windiness and precipitation varied. All these parameters have different effects on the GDGT signals in the lake.

Response: *Wind may influence the mixing regime in the short-term. However, a long-term wind record in this region is lacking and we hence could not compare it with our record. Based on the relationship between windy days and precipitation in Africa, there should be more windy days when the climate was dry and lake level was low. In this case, windy and dry climate would limit to growth of Thaumarchaeota in Lake Chenghai, resulting low %cren values and high GDGT-0/cren ratio. We feel this is too speculative to include in the paper.*

20) L336: How realistic is the reduced sensitivity of %cren at high lake level? How much variation in lake level do you expect? The %cren in your record varies between 0 and 60%, which would correspond with a lake level change of ~1000m based on the relation of Wang et al 2019. Is this feasible?

Response: *The absolute value of lake level reconstructed from the calibration is not feasible for Lake Chenghai, due to an outflow that would occur when the level increases to 1540 m a.s.l.. However, this calibration tells us that the relationshiop* *between water depth and %cren values in not linear, and the %cren values should be more sensitive to climate change when the lake-level was low.*

21) L344: I will refrain from providing detailed comments on the spatial context of the record, as there are currently too many aspects about it that are not well known or explained. In a next version however, do pay (more) attention to differences between the records and what they mean (are they really caused by climate or are they caused by comparing different proxies that record not exactly the same).

Response: *In the revised version, we have focused on the temperature records from the Indian monsoon region, and paid more attention to differences between these records and possible forcings of these differences (L438-454). Thank you for your constructive and helpful comments.*

~~Microbial~~Archaeal ~~Membrane Tetraether~~ lipid-inferred paleohydrology and paleotemperature of Lake Chenghai during the Pleistocene-Holocene transition

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ABSTRACT

Over the past few decades, paleoenvironmental studies in the Indian Summer Monsoon (ISM) region have mainly focused on precipitation change, with few published terrestrial temperature records from the region. We analyzed the distribution of isoprenoid glycerol dialkyl glycerol tetraethers (isoGDGTs) in the sediments of Lake Chenghai in southwest China across the Pleistocene–Holocene transition, to extract both regional hydrological and temperature signals for this important transition period. Lake-level was reconstructed from the relative abundance of crenarchaeol in isoGDGTs (%cren) and the crenarchaeol'/crenarchaeol ratio. The %cren-inferred lake-level identified a single lowstand (15.4-14.4 cal ka BP), while the crenarchaeol'/crenarchaeol ratio suggests relatively lower lake-level between 15.4-14.4 cal ka BP and 12.5-11.7 cal ka BP, corresponding to periods of weakened ISM during the Heinrich 1 ~~(H1)~~ and Younger Dryas ~~(YD)~~ cold event. A filtered TetraEther indeX consisting of 86 carbon atoms (TEX$_{86}$ index) revealed that lake surface temperature ~~reached~~ was similar to present-day values during the ~~YD cold event~~last deglacial period, and suggests a substantial warming of ~4 ℃ from the early Holocene to the mid-Holocene. Our paleotemperature record is generally consistent with other records in southwest China, suggesting that the distribution of isoGDGTs in Lake Chenghai sediments has potential for quantitative paleotemperature reconstruction.

Keywords: Quantitative temperature reconstruction; Lake-level; TEX$_{86}$; Isoprenoid GDGTs; Lacustrine sediment

1. Introduction

Precipitation variation in the Indian summer monsoon (ISM) region has ~~decreased substantially with recent global warming, greatly threatening~~a great threat to ecosystem function, water availability and economic security across the region (Sinha et al., 2011; Sinha et al., 2015; Ljungqvist et al., 2016). ~~For example, in 2009-2010 severe droughts occurred in southwest China that reduced food production dramatically (Lü et al., 2012).~~ This has stimulated growing scientific interest in understanding the underlying forcing mechanisms behind climate variability in the ISM region on different time-scale, in order to better predict future monsoonal variations.

Over the past two decades, climate evolution in the ISM region since the Last Glacial Maximum has been reconstructed from various paleoclimatic archives, including stalagmites, marine and lacustrine sediments (Dykoski et al., 2005; Rashid et al., 2007; Govil and Divakar Naidu, 2011; Saraswat et al., 2013; Contreras-Rosales et al., 2014; Wang et al., 2014b; Dutt et al., 2015; Wu et al., 2015; Kathayat et al., 2016; Zhang et al., 2017a, 2017b; Li et al., 2018; Zhang et al., 2018; Sun et al., 2019; Zhang et al., 2019). These studies provide evidence that changes in ISM precipitation ~~and temperature were generally synchronous~~ on the orbital- and millennial-scale, with a weakened ISM occurring during cold events, and strengthened ISM occurring during warm intervals.

~~However,~~ In addition to precipitation, temperature is an important climatic factor, due to its significant effects on the evaporation and regional hydrological cycle. ~~there~~ There is a still lack ~~remains a paucity~~ of quantitative reconstructions of ~~both hydrological and thermal parameters~~terrestrial temperature from the ISM region (Shen et al., 2006; Zhang et al., 2017a; Wu et al., 2018; Feng et al., 2019; Ning et al., 2019; Tian et al., 2019; Zhang et al., 2019~~),~~). During the last deglaciation-Holocene transition, the climate of high latitudes in the Northern Hemisphere is punctuated by three abrupt, millennial-scale events: the Heinrich 1 (H1) cold event, the Bølling/Allerød (BA) warm period and the Younger Dryas (YD) cooling (Alley and Clark, 1999). These intervals are attributed to a variety of mechanisms including changes to orbitally controlled insolation, ice sheet extent, oceanic circulation and atmospheric greenhouse gases (Alley and Clark, 1999). The recent quantitative summer temperature based on pollen and chironomids from southwest China have been developed to address the response of long-term temperature to the high latitude climate changes (Zhang et al., 2017 and 2019; Wu et al., 2018). However, the magnitudes of these temperature variations were not consistent, and further studies are required.~~which hinders our detailed understanding of the dynamics of the ISM and therefore the development of climate models with improved prognostic potential.~~

~~Pollen, chironomids, alkenone and g~~Glycerol dialkyl glycerol tetraethers (GDGTs) have been widely used for the quantitative reconstruction of terrestrial paleotemperature during the Quaternary due to the fact that they are ubiquitous in soils and lacustrine sediments (~~Nakagawa et al., 2003, 2006;~~ Blaga et al., 2013; ~~Stebich et al., 2015;~~ Wang et al., 2017b; ~~Zhang et al., 2017a; Sun et al., 2018; Wu et al., 2018;~~ Zheng et al., 2018; Ning et al., 2019; Tian et al., 2019~~; Zhang et al., 2019~~). Isoprenoid GDGTs (isoGDGTs), comprising acyclic or ring-containing isoprenoidal biphytanyl carbon chains, are a suit of membrane lipids produced by some species of archaea, such as Euryarchaeota, Crenarchaoeota and Thaumarchaeota ~~that are ubiquitous in soils, lacustrine and marine sediments~~ (Schouten et al., 2013). IsoGDGTs containing 0 to 3 cyclopentane moieties (isoGDGTs 0–3, Fig. S1) are common isoGDGTs with a large range of biological sources (Schouten et al., 2013). For example, Thaumarchaeota were the dominant biological source of GDGT-0 in Lake Lucerne from Switzerland (Blaga et al., 2011); while GDGT-0 in Lake Challa surface sediments might predominantly derive from archaea residing in the deeper, anoxic water column, such as the group 1.2 and marine benthic group C group of the Crenarchaeota, and the Halobacteriales of the Euryarchaota (Sinninghe Damsté et al., 2009); and methanogenic and methanotrophic archaea can also be two important sources of GDGT-0 within the water column and sediment (Blaga et al., 2009; Powers et al., 2010). In contrast, crenarchaeol and its regioisomer, crenarchaeol' (Fig. S1), are considered to be produced specifically by mesophilic Thaumarchaeota in aquatic environments (Schouten et al., 2002; Blaga et al., 2009; Kim et al., 2010; Powers et al., 2010; Schouten et al., 2013). ~~The distribution of isoGDGTs compounds correlates well with surface water temperature, and therefore has great potential for use as a paleotemperature proxy (Schouten et al., 2002; Blaga et al., 2009; Kim et al., 2010; Powers et al., 2010).~~ On this basis, the ratio of GDGT-0/crenarchaeol has been proposed to evaluate the influence of Thaumarchaeota on the distribution of isoGDGTs in lacustrine sediments, and the ratio typically varies between 0.2 and 2 in Thaumarchaeota (Schouten et al., 2002; Blaga et al., 2009).

Thaumarchaeota have a physiological mechanism to increase the weighted average number of cyclopentane rings in their membrane lipids with growth temperature (Schouten et al., 2002). Thus ~~The~~ the TetraEther indeX consisting of 86 carbon atoms (TEX$_{86}$ index), which represents the relative number of cyclopentane moieties in isoGDGT molecules derived from aquatic Thaumarchaeota, has great potential for use as a paleotemperature proxy ~~has also been successfully applied as a paleothermometer~~ in marine and large lakes (Tierney et al., 2008; Berke et al., 2012; Blaga et al., 2013; Wang et al., 2015). However, the index may not be a reliable proxy for past temperature in small lakes due to substantial amounts of soil and/or methanogenic archaea isoGDGTs identified in the same lacustrine sediment and variability in the depth of isoGDGT production in aquatic ecosystem (Blaga et al., 2009; Powers et al., 2010; Sinninghe Damsté et al., 2012a). It has also been shown that crenarchaeol' is only present in low abundance in most Thaumarchaeota except for the group I.1b Thaumarchaeota, where it is one of the major isoGDGTs (Kim et al., 2012; Sinninghe Damsté et al., 2012b). The crenarchaeol'/crenarchaeol ratios for enrichment cultures of group I.1a aquatic Thaumarchaeota are typically 0.01-0.04, however, for group I.1b Thaumarchaeota enriched from soils the crenarchaeol'/crenarchaeol ratios are around 0.21 and substantially higher (Pitcher et al., 2011; Sinninghe Damsté et al., 2012a). In addition, a likely Group I.1b Thaumarchaeota population inhabiting the subsurface water column near the anoxic-suboxic boundary was found in Lake Malawi, but the total production of isoGDGTs by this group appears to be much lower than the surface-dwelling Thaumarchaeota (Meegan Kumar et al., 2019).

In addition, aquatic Thaumarchaeota are nitrifers, that prefer to live above the oxycline of relatively deep lakes, as has been observed by a range of lipid biomarker and DNA based investigations of vertical changes in archaea communities in lake water columns (Sinninghe Damsté et al., 2009; Blaga et al., 2011; Schouten et al., 2012; Buckles et al., 2013; Meegan Kumar et al., 2019). Some Thaumarchaeota are considered to be suppressed by a high light level, which consequently might also prohibit them from thriving near the surface lakes (Schouten et al., 2013). In addition, Thaumarchaeota are chemoautotrophic and thrive predominantly near the oxycline in stratified lakes, mainly due to the release of ammonia derived from descending particulate organic matter that is recycled primarily by photoautotrophs or heterotrophs in the photic zone (Tierney et al., 2010). ~~the~~ Consequently, the proportion of crenarchaeol in isoGDGTs (cren%) has been suggested ~~to be a~~as lake-level proxy ~~due to a preference of the producer of this compound for a niche above the oxycline in the upper part of the water column in lacustrine systems~~ (Wang et al., 2014a; Wang et al., 2017a; Wang et al., 2019). However, suggested that mixing of the water column will be much more frequent at lowstand conditions, and therefore periodically or permanently oxic, high nutrient availability water and enhanced nitrogen cycling would be likely to result in a relatively higher production of crenarchaeol (Filippi and Talbot, 2005; Sinninghe Damsté et al., 2012).

In this study, we present an isoGDGT record spanning the last deglacial-Holocene transition from Lake Chenghai in the southwest China. Our stable oxygen isotope ($\delta^{18}O$) record of authigenic carbonates from Lake Chenghai previously revealed that drought events occurred from 15.6 to 14.4 cal ka BP and 12.5 to 11.7 cal ka BP corresponding to the H 1 and YD event (Sun et al., 2019). The present study aims were to (1) identify sources of isoGDGTs in Lake Chenghai sediments and their linkage, if any, with lake-level variation; (2) ~~We use the results to~~ test the reliability of isoGDGT-based proxies as ~~lake-level and~~ temperature indicators, by comparing our results with other paleoenvironmental records from adjacent areas, and explore the possible mechanisms driving temperature variations during the last deglaciation-Holocene transition in southwestern China.

2. Materials and methods

2.1. Regional setting

Lake Chenghai (26°27′-26°38′N, 100°38′-100°41′E, Fig. 1A) is a tectonic lake located ~~in Yongsheng County~~ in the northwestern part of Yunnan Province (Wang and Dou, 1998). The present water surface elevation ~~of the lake-level~~ is ~1500 m above sea level (a.s.l.), and the maximum water depth is ~35 m~~ with a mean depth of ~20 m~~. The lake is hydrologically closed at present, ~~has~~ with a surface area of ~77 km^2 ~~with~~ and a catchment of ~318 km^2 (Wu et al., 2004). However, Lake Chenghai was linked to the Jinsha River via the Haikou River~~ during the Ming Dynasty (1368-1644 CE), but became a closed lake in the 1690s CE when~~before a dam ~~(~~at an elevation of ~1540 m a.s.l.~~)~~ was constructed on its southern side at ~0.3 cal ka BP (Wang and Dou, 1998).The annual mean lake surface temperature (LST) is ~16 ℃ (Wan et al., 2005). In summer, the lake becomes thermally stratified, with the thermocline at between 10 to 20 m (Fig. 1C, Lu, 2018). ~~The lake water is slightly brackish (average= ~1‰) and alkaline (average pH= ~8). There are no perennial inlets or outflow streams at present, and t~~ Despite a relatively large catchment, the lake is mainly maintained by direct precipitation and groundwater, with a total dissolved solids of ~1‰ and–, pH of ~8 (Wan et al., 2005). The lake is eutrophic with total phosphate concentration of 0.05 mg/L, and total nitrogen concentration of 0.89 mg/L (Li et al., 2019). ~~Lake Chenghai was linked to the Jinsha River via the Haikou River during the Ming Dynasty (1368-1644 CE), but became a closed lake in the 1690s CE when a dam (~1540 m~~

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~~a.s.l.) was constructed on its southern side (Wang and Dou, 1998).~~

~~The lake basin is surrounded by mountains ranging from 2300-4000 m a.s.l.~~ Topsoil types ~~include~~ are lateritic red earths and mountain red brown soils in the catchment (Wang and Dou, 1998). The Lake Chenghia region is mainly affected by a warm-humid monsoonal airflow from the tropical Indian Ocean from June to September, and by the southern branch of the Northern Hemisphere westerly jet between October and May (Wang and Dou, 1998). The mean annual temperature is ~14 ℃, the mean annual precipitation is ~660 mm with 80% falling between June and September (~~Observed climatic data spanning the past 30 years from~~ the Yongsheng meteorological station ~~(~~26.68 °N, 100.75 °E; elevation of 2130 m a.s.l.)~~ indicate a mean annual temperature of 14 ℃, an annual precipitation of 660 mm, ~80% of which falls from June to September~~.

2.2. Sampling and dating

In summer 2016, ~~An~~ an 874-cm-long sediment core (CH2016) was retrieved ~~at 26° 33′ 29.4″ N, 100° 39′ 6.7″ E~~ using a UWITEC coring platform system with a percussion corer in 30 m of water depth ~~in July 2016 CE~~ (26° 33′ 29.4″ N, 100° 39′ 6.7″ E)~~. The water depth was 30 m. The sediment cores~~Each section of the core ~~were~~ was split ~~longitudinally~~lengthways, photographed and then sectioned at a 1-cm interval in the laboratory~~, and~~; the samples stored at 4 ℃ until analysis.

The chronology was established using accelerator mass spectrometry (AMS) ^{14}C dating of eight terrestrial plant macrofossils and charcoal (Sun et al., 2019). ~~Macrofossils of leaves, woody stems and charcoal were hand-picked under the microscope. Eight dates covering the period from the last deglaciation to early Holocene were obtained.~~ The radiocarbon analyses were performed at the Beta Analytic Radiocarbon Dating Laboratory in Miami, USA. The age model was developed utilizing Bacon, implemented in R 3.1.0 at 5-cm intervals (Blaauw and Andres Christen, 2011; R Development Core Team, 2013). All AMS ^{14}C dates were calibrated to calendar years before present (0 BP =1950~~ CE~~) using the program Calib

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7.1 and the IntCal13 calibration data set (Reimer et al., 2013). The basal mean weighted age is ~15.6 cal ka BP (Fig. 2, Sun et al., 2019).

2.3. Lipid extraction and analysis

A~~fter freeze-drying, a~~ total of 102 freeze-dried samples at 4-cm interval ~~over the Pleistocene-Holocene transition~~ were collected for GDGT analysis over the the last deglaciation-Holocene transition~~,~~. The sampling resolution ~~and this~~ was increased to 1-cm ~~resolution across~~between 792-806 cm, ~~span~~ due to the low sedimentation rate observed in this section~~over this interval~~. In addition, seven surface (the top 2 cm) sediments covering the whole lake sampled in 2014 were analyzed. Lipid extraction was determined according to the procedures in Feng et al (2019). A ~4 g aliquot ~~of~~ each sample was extracted ultrasonically (4 times) with a mixture of dichloromethane and methanol (9:1, v/v). The supernatants were condensed and ~~base hydrolyzed~~saponified at room temperature for 12 h ~~in~~ with a 1 M KOH/methanol solution. The neutral fractions were then separated into apolar and polar fractions on a silica gel column, using *n*-hexane and methanol, respectively. The polar fraction containing the GDGTs was concentrated and filtered through 0.45 μm polytetrafluoroethylene syringe filters using *n*-hexane/ isopropanol (99:1 v/v)~~. These fractions were~~, and then dried in N_2~~ and stored at -20 ℃ until further analysis~~.

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GDGTs were analyzed using an Agilent ~~1200~~ 1260 series high performance liquid chromatography-atmospheric pressure chemical ionization-mass spectrometer (HPLC- APCI-~~–~~ MS), following the procedure of Yang et al. (2015) at the Institute of Tibetan Plateau Research, Chinese Academy of Sciences. Briefly, the GDGTs were separated using three silica columns in tandem (~~150~~ 100 mm× 2.1 mm, 1.9 μm; Thermo ~~Finnigan~~Fisher Scientific, U.S.A.), maintained at 40 ℃. The elution gradients were 84% *n*-hexane (A): 16% ethyl acetate (B) for 5 min, 84/16 to 82/18 A/B for another 60 min, then to 100% B for 21 min and kept for 4 min, followed by a return to 84/16 A/B for 30 min. The total flow rate of pump A and pump B was maintained at 0.~~1~~ 2 ml/min. The APCI-MS conditions were: vaporizer pressure 60 psi, vaporizer temperature 400 ℃, drying gas flow 6 L/min and temperature 200 ℃, capillary

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voltage 3500 V and corona current 5 μA (~3200 V). Selected ion monitoring (SIM) mode was performed to target specific *m/z* values for each GDGT compound, including 1302 (GDGT-0), 1300 (GDGT-1), 1298 (GDGT-2), 1296 (GDGT-3), ~~1294 (crenarchaeol),~~ and 1292 (crenarchaeol and crenarchaeol’)~~, 1050 (IIIa, IIIa’), 1048 (IIIb, IIIb’), 1046 (IIIc, IIIc’), 1036 (IIa, IIa’), 1034 (IIb, IIb’), 1032 (IIc, IIc’), 1022 (Ia), 1020 (Ib) and 1018 (Ic). The chemical structures of these compounds are presented in Supplementary Fig. S1.~~ The results are presented as the fractional of the sum of the isoGDGTs ~~or the sum of the branched GDGTs (brGDGTs),~~ based on the integration of the peak areas of the $[M+H]^+$ ions.

2.4. Index calculation and temperature reconstruction

The percentage of each isoGDGT (X) was calculated according to the following equation:

%X= X/ (GDGT-0+ GDGT-1+ GDGT-2+ GDGT-3+ crenarchaeol+ crenarchaeol’) (1)

The TEX$_{86}$ index was defined by Schouten et al. (2002) as follows:

TEX$_{86}$= (GDGT-2+ GDGT-3+ crenarchaeol’)/ (GDGT-1+ GDGT-2+ GDGT-3+ crenarchaeol’) (2)

TEX$_{86}$-inferred LST was calculated using the global lake calibration of Castañeda and Schouten (2015):

LST= 49.03 × TEX$_{86}$- 10.99 (r^2= 0.88, n=16, RMSE= 3.1 ℃) (3)

~~The ratio of branched to isoprenoid tetraethers (BIT index), used as an indicator of soil organic matter input and as a test of the utility of the TEX$_{86}$ paleotemperature proxy, was calculated following Hopmans et al. (2004):~~

~~BIT= (Ia+ IIa+ IIa’+ IIIa+ IIIa’)/ (Ia+ IIa+ IIa’+ IIIa+ IIIa’+ crenarchaeol) (4)~~

3. Results

~~A wide variety of isoGDGT compositions is present in the sediments of Lake Chenghai~~IsoGDGTs composition varied greatly in Lake Chenghai sediments. As illustrated in Fig. 3, GDGT-0 is the most abundant isoGDGT composition of the surface sediments. ~~the~~ The relative abundance of GDGT-0 (%GDGT-0) ranged from 71.6- 94.4 with a mean of 89.2%, the %cren values varied from 3.8- 18.1% with a mean of 7.6%. The ratios of GDGT-0/crenarchaeol were from 4.0-24.5 with a mean of 15.5. The average values of GDGT-1, GDGT-2 and GDGT-3 relative abundance were 1.2, 1.1 and 1.4%, respectively. The crenarchaeol's regioisomer, crenarchaeol', occurred in only low abundance, most close to the detection limit, and therefore TEX$_{86}$ values could not be calculated for these surface sediments.

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The ~~relative abundances of crenarchaeol (~~%cren~~)~~ values ranged ~~from~~ between 2.4-61.3% with a mean of 52.4% in the core CH2016. The %cren values were relatively low and highly variable during 15.4-14.4 cal ka BP, ranging ~~from~~ between 1.8-32.0%, with a mean of 11.6%. By contrast, the values were relatively stable during 14.4-7.0 cal ka BP, ranging ~~from~~ between 41.8-61.3% with a mean of 58.3%. The relative abundances of ~~its regioisomer,~~ crenarchaeol'~~,~~ had a mean of 1.7%. The ratios of crenarchaeol'/crenarchaeol were highly variable during 15.4-14.4 cal ka BP with a mean of 0.07. After this time, the values gradually decrease during 14.4-11.7 cal ka BP time interval with a minor ~~reversal~~ increase ~~during~~ between 12.5-11.7 cal ka BP, where the ratio averaged 0.05. The crenarchaeol'/crenarchaeol ratios were generally stable and fluctuated around 0.03 during the period 11.8-7.0 cal ka BP.

The relative abundances of GDGT-0 (%GDGT-0) showed a significant negative correlation with the ~~reciprocal of~~ %cren in the core CH2016 (r^2= 0.~~98~~99, p< 0.001). The %GDGT-0 values had a mean of 74.0% ~~during~~ between 15.4-14.4 cal ka BP and a mean of 19.6% during the 14.4-7.0 cal ka BP interval. The ~~ratios~~ values of GDGT-0/crenarchaeol were generally >2 during the period 15.4-14.4 cal ka BP, ranging from 1.4-49.9 with a mean of 16.7, and all <2 from 14.4-7.0 cal ka BP. The relative abundance of GDGT-1, GDGD-2 and GDGT-3 were generally low in the sediments, with ~~a~~ means of 8.9, 9.2, and 1.3, respectively.

The TEX_{86} values were also highly variable during 15.4-14.4 cal ka BP period, ranging ~~from~~ between 0.36-0.68 with a mean of 0.54. Thereafter, the values generally followed an increasing trend, ranging ~~from~~ between 0.49-0.63 with a mean of 0.58. ~~The BIT values exhibited a significant negative correlation with cren% values (r^2= 0.94, p< 0.001), ranging from 0.39-0.99 with a mean of 0.54. An abrupt decrease from 0.96 to 0.52 occurred at 14.4 cal ka BP. After this time, the BIT values gradually decreased to a minimum value at 9.3 cal ka BP, and fluctuated thereafter around 0.48 during 9.3-7.0 cal ka BP.~~

4. Discussion

4.1. ~~Environmental significances of the isoGDGT-based proxies~~Provenance of isoGDGTs

In order to evaluate the potential sources of isoGDGTs in Lake Chenghai sediments, we plotted a ternary diagram to compare the distribution patterns of GDGT-0, crenarchaeol, and the sum of GDGT-1, GDGT-2, GDGT-3, and crenarchaeol' (‘TEX_{86}’ GDGT) among our samples, previously published Chinese soils and global marine sediments compiled by Yao et al. (2019), and previously published Chinese lacustrine surface sediments (Günther et al., 2014; Dang et al., 2016; Hu et al., 2016; Li et al., 2016, 2019; Yao et al., 2019; Wang et al., 2020). In Lake Chenghai surface sediments, GDGT-0 is the predominant component among the isoGDGTs, consistent with most previous studies of lacustrine sediments (Blaga et al., 2009; Dang et al., 2016; Li et al., 2019; Yao et al., 2019; Wang et al., 2020). For example, GDGT-0 can account for more than 90% of total isoGDGTs in most shallow lake surface sediments from East China (Dang et al., 2016); ~80% in saline pond surface sediments from northeast China (Li et al., 2019), and ~54% in surface sediments from the Qinghai-Tibetan Plateau (Wang et al., 2020). The values of GDGT-0/cren >2 in Lake Chenghai surface sediment generally reflect non-thaumarchaeotal isoGDGTs were also likely to be an important source in this lake system. The distribution of isoGDGTs between Chinese lacustrine surface sediments and soils were similar, and both were generally higher than that in global marine sediments and Thaumarchaeota. This line of evidence also suggests that the surface sediments could contain a significant contribution of soil isoGDGTs input (Li et al., 2016; Li et al., 2019).

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~~Crenarchaeol and its regioisomer are considered to be produced specifically by mesophilic Thaumarchaeota in aquatic environments (Schouten et al., 2002; Schouten et al., 2013).~~

The distribution of isoGDGT in Lake Chenghai sediment from 15.4-14.4 cal ka BP was similar to that of the surface sediments, suggesting a substantial contribution of non-thaumarchaeota during this period. However, the relative abundance of GDGT-0 significantly decreased and %cren increased in Lake Chenghai sediments from 14.4-7.0 cal ka BP. The plots generally overlapped with those of global marine sediments and Thaumarchaeota in the ternary diagram, indicating that Thaumarchaeota dominated the archaea community in Lake Chenghai during the late glacial period and the early Holocene. Thhe observed down-core changes in crenarchaeol’/crenarchaeol ratios may be due to relatively high contributions of group I.1b Thaumarchaeota from soils during 15.4-11.8 cal ka BP, and that these dominate the contributions of isoGDGTs derived from aquatic group I.1a Thaumarchaeota during the period from 11.8-7.0 cal ka BP.

~~In marine conditions, Thaumarchaeota have a physiological mechanism to increase the weighted average number of cyclopentane rings in their membrane lipids with growth temperature, thus a significant linear correlation is found between~~ ~~TEX_{86}~~ ~~values and mean annual sea surface temperature (Schouten et al., 2002). In the studies of lacustrine systems, the temperature calibration of~~ ~~TEX_{86}~~ ~~has been found to be nearly identical to the marine calibration, suggesting that the paleothermometer can also be applied in lacustrine sediments (Powers et al., 2004; Blaga et al., 2009; Powers et al., 2010; Castañeda and Schouten, 2011). In addition, aquatic~~

~~Thaumarchaeota are nitrifers, that prefer to live above the oxycline of relatively deep lakes, as has been observed by a range of lipid biomarker and DNA based investigations of vertical changes in archaea communities in lake water columns (Sinninghe Damsté et al., 2009; Blaga et al., 2011; Schouten et al., 2012; Buckles et al., 2013; Meegan Kumar et al., 2019).~~

~~Some Thaumarchaeota are considered to be suppressed by a high light level, which consequently might also prohibit them from thriving right near the surface layer of lake water (Schouten et al., 2013). In addition, Thaumarchaeota are chemoautotrophic and thrive predominantly near the oxycline in stratified lakes, mainly due to the release of ammonia derived from descending particulate organic matter that is recycled primarily by photoautotrophs or heterotrophs in the photic zone (Tierney et al., 2010). Furthermore, mixing of the water column will be much more frequent at lowstand conditions (Filippi and Talbot, 2005), and therefore periodically or permanently oxic, high nutrient availability water and enhanced nitrogen cycling would be likely result in a relatively lower production of crenarchaeol. Therefore, the cren% value measure in lacustrine sediments has been proposed to be a potential proxy for lake level change, with high values indicating highstand and deep lake status, while low values reflecting lowstand and shallow lake status (Wang et al., 2014a; Wang et al., 2017a; Wang et al., 2019).~~

~~Although~~ ~~TEX_{86}~~ ~~and cren% show great potential as paleotemperature and paleo-lake-level proxies, they may be significantly biased when a substantial amount of soil and/or methanogenic archaea isoGDGTs are identified in the same lacustrine sediment (Weijers et al., 2006; Blaga et al., 2009; Powers et al., 2010; Wang et al., 2019). BIT index values are generally >0.90 in soils, whereas values are close to zero for large lake sediments (Hopmans et al., 2004; Weijers et al., 2006). In this study, Lake Chenghai sediment the BIT index values range from 0.39-0.99, indicating that a considerable proportion of isoGDGTs could derive from soils. However, recent studies of modern processes in a wide variety of lakes have suggested that at least partly branched GDGTs are generated by *in-situ* production (Blaga et al., 2010;~~

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~~Tierney et al., 2010; Pearson et al., 2011; Hu et al., 2016; Dang et al., 2018; Russell et al., 2018). Therefore, *in-situ* production of branched GDGTs in Lake Chenghai cannot be fully excluded.~~

~~It has also been shown that crenarchaeol' is only present in low abundance in most Thaumarchaeota except for the group I.1b Thaumarchaeota, where it is one of the major GDGTs (Kim et al., 2012; Sinninghe Damsté et al., 2012b). The crenarchaeol'/crenarchaeol ratios for enrichment cultures of group I.1a aquatic Thaumarchaeota are typically 0.01-0.04, however, for group I.1b Thaumarchaeota enriched from soils the crenarchaeol'/crenarchaeol ratios are around 0.21 and substantially higher (Pitcher et al., 2011; Sinninghe Damsté et al., 2012a). This suggests that the observed down-core changes in crenarchaeol'/crenarchaeol ratios may be due to relatively high contributions of group I.1b Thaumarchaeota from soils during 15.4-11.8 cal ka BP, and that these dominate the contributions of isoGDGTs derived from aquatic group I.1a Thaumarchaeota during the period from 11.8-7.0 cal ka BP.~~

~~The TEX$_{86}$ and cren% measures might also be affected by methanogenic and methanotrophic archaea because methanogenesis is the dominant anaerobic metabolic pathway in freshwater ecosystems (Blaga et al., 2009; Dang et al., 2016; Yao et al., 2019). Crenarchaeol and GDGT-0 can be derived from Group I Thaumarchaeota, whereas methanogens synthesize GDGT-0, but no crenarchaeol. On this basis, the ratio of GDGT-0/crenarchaeol has been proposed to evaluate the influence of methanogenesis on the distribution of isoGDGTs in lacustrine sediments (Blaga et al., 2009). The ratio typically varies between 0.2 and 2 in group I Thaumarchaeota, thus a value >2 is generally thought to reflect a substantial contribution from methanogens to the total isoGDGT (Schouten et al., 2002; Blaga et al., 2009). Therefore, higher GDGT-0/crenarchaeol values suggest that methanogenic and methanotrophic archaeal were also likely to be an important source of GDGTs in some of Lake Chenghai sediments during 15.4-14.4 cal ka BP.~~

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4.2. Assessment of isoGDGT-based lake-level proxy

Environmental ~~changes~~ implication of ~~at Lake Chenghai as inferred from~~ %cren at Lake Chenghai~~, crenarchaeol'/crenarchaeol ratio, the BIT index and GDGT-0/crenarchaeol ratio~~ during the period from the last deglaciation to the early Holocene ~~are~~ was illustrated in Fig. ~~4~~5. The relatively low %cren ~~and high GDGT-0/crenarchaeol~~ values during 15.4-14.4 cal ka BP is consistent in timing with the δ^{18}O record of authigenic carbonates derived from the same core (Fig. 4e, Sun et al., 2019), speleothem δ^{18}O records from Mawmluh Cave and Bittoo Cave in north India (Fig. 4f, Dutt et al., 2015; Kathayat et al., 2016), and Donnge Cave in southwest China (Dykoski et al., 2005), which all record a substantial positive shift in δ^{18}O values at that time. Speleothem δ^{18}O records in the ISM region are used as a rainfall amount proxy, tracking changes in monsoon intensity (Dykoski et al., 2005; Cheng et al., 2012; Dutt et al., 2015). This suggests that the Thaumarchaeota were mainly suppressed by non-thaumarchaeotal ~~methanogenic and methanotrophic~~ archaeal. ~~Deep lake conditions and thermal stratification have also been suggested as important in influencing the Thaumarchaeota's growth, while any increase in water column turbulence would have negatively affected them (Tierney et al., 2010).~~ Thus the abrupt increase in %cren values at 14.4 cal ka BP ~~suggest~~ indicates a ~~lowland~~ lowstand of Lake Chenghai during 15.4-14.4 cal ka BP, and a highstand period thereafter.

The interpretation of %cren contradict the case for Lake Challa, but consistent with that for Lake Qinghai in northwest China (Sinninghe Damsté et al., 2012; Wang et al., 2014). This difference is possibly due to the different response of Thaumarchaeota in the two types of lakes to the mixing regime. For the small and deep Lake Challa, there is never complete mixing due to the stable stratification of the warmer water column and the lack of seasonality (Sinninghe Damsté et al., 2009). Below the oxycline nitrate level was high, more substantial mixing regenerates more nutrients to the surface waters, resulting a relatively higher production of crenarchaeol (Sinninghe Damsté et al., 2012). In contrast, Lake Chenghai and Lake Qinghai are

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seasonal mixing lakes, and the vertical change of nutrients may be relatively small in the lake water. In addition, the low lake level during the H1 event was associated with the weakened ISM, less terrestrial nutrient input leads to suppress the growth of Thaumarchaeota and reduce the production of crenarchaeol.

~~The lowstand period is consistent in timing with the stable oxygen isotope (δ^{18}O) record of authigenic carbonates derived from the same core (Fig. 4e, Sun et al., 2019), speleothem δ^{18}O records from Mawmluh Cave and Bittoo Cave in north India (Fig. 4f, Dutt et al., 2015; Kathayat et al., 2016), and Donnge Cave in southwest China (Dykoski et al., 2005), which all record a substantial positive shift in δ^{18}O values at that time. Speleothem δ^{18}O records in the ISM region are used as a rainfall amount proxy, tracking changes in monsoon intensity (Dykoski et al., 2005; Cheng et al., 2012; Dutt et al., 2015). Therefore, the lowstand of Lake Chenghai during 15.4-14.4 cal ka BP implies a weakened ISM during the Heinrich 1 (H1) cold event, consistent with other evidence.~~

Low lake-levels and weakened ISM during the H1 cold event are also ~~indicated by~~observed in several previous paleolimnolgical studies from the Yunnan Plateau, within the uncertainties of the age model. Diatom and grain-size records from Lake Tengchongqinghai show a significant decrease in acidophilous diatom species and an increase in the grain-size of mineral particles from 18.5 to 15.0 cal ka BP, suggesting that the climate was ~~driest~~ dry and the ISM was at its weakest since the last deglaciation (Fig. 4g, Zhang et al., 2017b; Li et al., 2018). Similarly, an increase in >30 μm grain-size particles in the late glacial sediments from Lake Xingyun reflects a period of abrupt weak ISM during the H1 cold event (Wu et al., 2015). In Lake Lugu, the loss of the planktonic diatoms and a switch to small *Fragilaria* spp. suggest a weaker stratification ~~during~~ from 24.5~~-~~ to 14.5 cal ka BP, which might also correspond to low lake-level at that time (Wang et al., 2014b). In addition, there is a peak of cren% centered at ~15.2 cal ka BP, suggesting a centennial high lake-level and strengthened ISM period, which was not identified by previous δ^{18}O record of authigenic carbonates (Sun et al., 2019). However, the strengthened ISM event at

~15.2 cal ka BP was clearly recorded by speleothem δ^{18}O record from Dongge Cave in southwest China (Dykoski et al., 2005).

Lake levels inferred from %cren do not show a lowstand during the YD, which is generally recognised as a period of low rainfall due to the weakening of the ISM~~Lake Chenghai lake-level does not seem to reduce during the Younger Dryas (YD) cold event, which is also recognized as a millennial-scale period of weak ISM~~ (Dutt et al., 2015; Dykoski et al., 2005; Kathayat et al., 2016; Sun et al., 2019). In contrast, a low lake-level signal is observed in the δ^{18}O record of authigenic carbonates from Lake Chenghai (Sun et al., 2019). In addition, increased lake water alkalinity and decreased lake-level are also recorded in the diatom and grain-size proxy records ~~during~~ between 12.8-11.1 cal ka BP of Lake Tengchongqinghai (Fig. 4g, Zhang et al., 2017b; Li et al., 2018). The inferred high lake levels during the YD which is inconsistent with a weakened ISM inferred from other proxies, might be due to the erosion of soil organic matter into the lake at this period (Wang et al., 2019). The crenarchaeol are relatively abundant in topsoils from southwest China, and the influence of soil input should be more significant at times of drier conditions (Yang et al., 2019). It is also worth noting that the crenarchaeol'/crenarchaeol ratios were not only relatively higher during the H1 cold event, but also showed a minor reversal during the YD cold event. These results are consistent with group I.1b Thaumarchaeota being an important source of isoGDGTs in small lakes and in the nearshore areas of large lakes (Wang et al., 2019).

Another possibility for the unexpected H1 and YD lake level is the ~~The differences in lake hydrological conditions to the YD weak ISM inferred from different lake sediment records is possibly due to differences in the~~ sensitivity of the proxy to lake-level variation in the case of Lake Chenghai.

The δ^{18}O record of authigenic carbonates from Lake Chenghai and speleothem δ^{18}O records in the ISM region suggest that the weakening of the ISM during the YD was less marked than that occurring during the H1 event, in turn suggesting that lake-levels in southwest China may have been higher during the YD than the H1 event (Dykoski et al., 2005; Dutt et al., 2015; Kathayat et al., 2016; Sun et al., 2019; Zhang et al., 2019). For the %cren proxy, we note that the values are ~~significantly~~ correlated to the logarithm of depth~~ in Asian lakes (%cren= 19.59×log(depth)+ 9.23)~~, suggesting that %cren may be less sensitive to water depth variation when the lake-level is relatively high, and more sensitive to water depth variation when the lake-level is relatively low (Wang et al., 2019). ~~It is also worth noting that the crenarchaeol'/crenarchaeol ratios were not only relatively higher during the H1 cold event, but also showed a minor reversal during the YD cold event. These results are consistent with group I.1b Thaumarchaeota being an important source of isoGDGTs in some small lakes and to the nearshore area of large lakes (Wang et al., 2019).~~

4.3. Warming in the ~~early~~ last deglaciation-Holocene transition

~~Robust~~ The application of the TEX_{86}-based paleotemperature calibration ~~critically~~ depends critically on the assumption that the isoGDGTs used for calculation of TEX_{86} values are mainly been derived from group I.1a in the water column (Blaga et al., 2009; Castañeda and Schouten, 2011; Powers et al., 2010; Sinninghe Damsté et al., 2012a). Since the influence of methanogenic archaea in the water column or archaea in the catchment soils have been recognized, Lake Chenghai sediments with crenarchaeol'/crenarchaeol ratios~~BIT values~~ >~~0.5~~0.04 and/or GDGT-0/crenarchaeol ratio >2 are excluded from the discussion below (Powers et al., 2010; Castañeda and Schouten, 2015). The ratio of branched GDGTs to isoGDGTs should be <0.5 if the TEX_{86}-temperature calibration in previous studies, because the values are generally >0.90 in soils, whereas values are close to zero for sediments from large lakes (Hopmans et al., 2004; Weijers et al., 2006). However, recent studies of a wide variety of lakes have suggested that at least some of the branched GDGTs can be produced *in situ* to the lake (Blaga et al., 2010; Tierney et al., 2010; Pearson et al., 2011; Hu et al., 2016; Dang et al., 2018; Russell et al., 2018). Therefore, *in situ* production of branched GDGTs in Lake Chenghai cannot be fully excluded, and the ratio of branched GDGTs to isoGDGTs was ignored in this study. ~~57~~ 74 samples remain that have isoGDGT distributions consistent with their dominant source being

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the aquatic Thaumarchaeota, most of these being from the time interval between 11.7-~~8.2~~7.0 cal ka BP, and only a few from the ~~early YD period (n=2) and 8.2-7.0 cal ka BP~~last deglaciation (n= 6). Using Equation 4 developed by Castañeda and Schouten (2015) to calculate mean LST, yielded LST values from ~~15.7~~14.3-20.1 ℃, with a mean of ~~17.9~~18.0 ℃ (Fig. 5a).

LST was \~~~15.8~~15.9 ℃ during the ~~early YD period~~last deglacial period, a temperature approaching the 16 ℃ observed in the present Lake Chenghai. ~~Following the YD cold event, LST rapidly increased from 16.2 ℃ at 11.2 cal ka BP to 18.2 ℃ at 11.0 cal ka BP, and LST ranged from 16.8 ℃ to 20.1 ℃ with a an increasing trend observed during the 11.0-7.0 cal ka BP interval.~~ Considering the TEX$_{86}$-based LST transfer function has a RMSE of 3.1 ℃, ~~This~~ this result is consistent with other recent reconstructed mean annual temperatures (MAT) in southwest China, which show the temperatures during the ~~YD cold event~~last deglaciation were generally similar to the present-day values~~,~~. For example, the MAT inferred from branched GDGTs from Lake Tengchongqinghai in southwest China increased episodically from 12.0 ℃ to 14.0 ℃ between 19.2 and 10.0 cal ka BP, where the modern mean annual temperature is 14.7 ℃ (Tian et al., 2019). The TEX$_{86}$-based deglacial LST and MAT inferred from branched GDGTs from Nam Co in south Tibetan Plateau also reported values simila to the present-day (Günther et al., 2015). Furthermore, the July temperature derived from the chironomid record from Lake Tiancai, and pollen record from Lake Yidun showed that the climate during the deglacial period was ~2-3 ℃ cooler relative to today (Fig. 5b and c, Shen et al., 2006; Zhang et al., 2019). The amplitudes of reconstructed terrestrial temperatures change in the Indian summer monsoon region are generally consistent with those from the tropical Indian Ocean. Although estimates of sea surface temperatures in the Andaman Sea and Bay of Bengal were variable, the cooling ranged from 1-4 ℃ (Rashid et al., 2007; MARGO, 2009; Govil and Naidu, 2011; Gebregiorgis et al., 2016).

Following the YD cold event, LST ranged from 16.2 ℃ to 20.1 ℃ with an increasing trend, and the middle Holocene was generally warmer than the early

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Holocene (11.7- 8.2 cal ka BP). In the Indian summer monsoon region, the reconstructed MAT using the branched GDGT calibration from Lake Ximenglongtan remained at ~12.5 ℃ from 9.4-7.6 cal ka BP, then experienced a rapid warming to 13.8 ℃ from 7.6-5.5 cal ka BP (Ning et al., 2019). Meanwhile, the branched GDGTs-MAT from Lake Tengchongqinghai also achieved its highest the highest value at around 7.1 cal ka BP (~~;~~Tian et al., 2019). Similarly, summer temperatures reconstructed from Lake Tiancai and Lake Xingyun also displayed lower values in the early Holocene when compared with that in the following millennium, though the amplitude of change is much lower (0.3 and 1.1 ℃ lower, respectively, Zhang et al., 2017a; Wu et al., 2018). The amplitude of the absolute scale of cooling and warming is of a lower magnitude in the chironomid, pollen and branched GDGT records as compared to the TEX_{86}-based reconstruction from Lake Chenghai. This may be due to the difference in the accuracy and precision of the proxy-based models, which also depend on the biological and seasonal sensitivity of the proxy, to constrain the absolute temperature values (Zhang et al., 2017).

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We also noted that most of the lake records from not only the Indian summer monsoon region, but other parts of east Asia, showed a thermal optimum at 8.0-7.0 cal ka BP (Ning et al., 2019). The summer isolation over the Northern Hemisphere, which is an important external forcing, was highest at ~11.0 cal ka BP, leading the temperature optimum in east and south Asia by 3-4 ka (Berger and Loutre, 1991). This indicates that additional feedback between solar insolation and internal processes, such as the persistence of remnants of the Northern Hemisphere ice-sheets during the early Holocene, should be considered (Ning et al., 2019). The Laurentide and Fennoscandian ice-sheets in the early Holocene enhanced surface albedo and reduced air temperature in the high latitudes, which likely led to enhanced westerlies transporting more cold air from the North Atlantic Ocean downward to the Indian monsoon affected regions of southwest China and north India through its south branch flow (Ning et al., 2019). In addition, the melting of ice-sheets is likely to have slowed down the Atlantic Meridional overturning circulation. The process could further result in relatively weakened Indian summer monsoon, and a reduction in heat was transported to the continent during the early Holocene (Zhang et al., 2017a). ~~For example, mean annual temperatures were 1.3 ℃ higher between 7.6 and 5.5 cal ka BP than during 9.4-7.6 cal ka BP as inferred from the branched GDGT record from Lake Ximenglongtan in southwest China (Fig. 5d, Ning et al., 2019). Furthermore, the July temperature derived from the chironomid record from Lake Tiancai and the pollen record from Lake Xingyun also show similar values during the YD cold event with that of the present-day (Fig. 5b and c, Wu et al., 2018; Zhang et al., 2019). The pollen record from Lake Xingyun in southwest China suggested that the July temperatures remained high values at ~25.5 ℃ during 8.0-5.5 cal ka BP, and ~1.6 ℃ higher than those during the early Holocene (Wu et al., 2018). However, July temperatures reconstructed from Lake Tiancai in southwest China display much lower amplitude of change, being only 0.3 ℃ higher during the mid-Holocene than the early Holocene (Zhang et al., 2017a).~~

~~Temperature in areas affected by the East Asian summer monsoon was more sensitive to high latitude climate change than in the ISM region. The mean annual temperature was ~8.5 ℃ cooler than present day during 12.3-11.3 cal ka BP in southwest Japan as inferred from the pollen record from Lake Suigetsu, with the variation larger in winter than summer (Fig. 5f, Nakagawa et al., 2003, 2006). The mean annual temperature estimated from the branched GDGTs record from the Shuizhuyang peat bog in southeast China dropped to 10.3 ℃ during the YD cold period, ~5.5 ℃ cooler than present-day (Wang et al., 2017b). In addition, a pollen record from Lake Sihailongwan in northeast China suggests a cool mixed forest biome was the dominant vegetation type during the late YD period, leading to the calculation of a mean July temperature of ~15-16 ℃, 5-6 ℃ cooler than modern July temperature (Fig. 5e, Stebich et al., 2015). The summer LST of Lake Sihailongwan reconstructed from long-chain alkenones shows the average temperature was ~14.2 ℃ during the YD event, ~4.3 ℃ cooler than the modern instrumental water temperature (Sun et al., 2018). Following the YD cold event, the pollen record from~~

~~Lake Sihailongwan in northeast China suggests that the July temperatures gradually increased from 18.0 ℃ at 11.4 cal ka BP to 26.5 ℃ at 8.1 cal ka BP, and remained at generally high values (>25.0 ℃) during the mid-Holocene (Stebich et al., 2015). The branched GDGTs record from Gushantu peat bog in northeast China also shows the highest mean annual temperatures occurred between 8.0 and 6.8 cal ka BP (Zheng et al., 2018). The regionally warmer mid-Holocene is considered to be related to the persistence of remnants of the Northern Hemisphere ice-sheets during the early Holocene, which slowed down the Atlantic Meridional overturning circulation and enhanced the westerlies, resulting in lower temperatures across the downstream Eurasian continent (Zhang et al., 2017a; Wu et al., 2018; Ning et al., 2019).~~

5. Conclusions

The record of isoGDGTs in the sediments of Lake Chenghai in southwest China presented in this study allows us to test the ability of isoGDGT-based proxies in the ISM region to reconstruct lake-level and temperature during the ~~Pleistocene~~last deglaciation-Holocene transition. The lake-level history inferred from %cren shows a relative lowstand of Lake Chenghai during 15.4-14.4 cal ka BP, corresponding to a period of weakened ISM during the H1 cold event. The indistinct signal of lake-level variation during the YD cold event may be due to the ~~%cren proxy not being sensitive to lake-level change when the lake was relatively full. By contrast, the crenarchaeol'/crenarchaeol ratios suggest~~ group I.1b Thaumarchaeota being an important source of isoGDGTs and consequently the lake level ~~was~~ may have been low during the YD cold event. After filtering for the influence of isoGDGTs derived from soils in the surrounding catchment and non-thaumarchaeota~~methanogens~~, the TEX_{86} paleothermometry revealed that the LST of Lake Chenghai was similar to the present-day value during the ~~YD cold event~~last deglaciation. ~~and~~ The lake also experienced a substantial warming of ~4 ℃ from the early-Holocene to the mid-Holocene due to the melting of the remnants of the continental ice-sheets in the Northern Hemisphere, which gradually reduced winter westerly circulation. Overall, our results show that ~~the distribution~~records of isoGDGTs in Lake Chenghai sediments ~~do~~ have potential for quantitative paleotemperature reconstruction once potential underlying biases are properly constrained.

Data availability.

All data in this study will be made available on request.

Author contributions.

W.S and E.Z designed the study, W.S performed the fieldwork and lab analysis. W.S and E.Z led the writing of the paper, J.C, J. S, M.I.B, C.Z, Q.J and J.S contributed to data interpretation and paper writing. All authors contributed to discussions and writing of the manuscript. The authors declare that they have no competing financial interests.

Competing interests.

The authors declare that they have no conflict of interest.

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References

Alley, R.B., Clark, P.U.: The deglaciation of the northern hemisphere: A global perspective. Annu. Rev. Earth Pl. Sc. 27, 149-182, DOI: 10.1146/annurev.earth.27.1.149.

Berger, A., Loutre, M.-F.: Insolation values for the climate of the last 10 million years.

Quaternary. Sci. Rev. 10, 297-317: DOI: 10.1016/0277-3791(91)90033-Q.

Berke, M.A., Johnson, T.C., Werne, J.P., Schouten, S., Sinninghe Damsté, J.S.: A mid-Holocene thermal maximum at the end of the African Humid Period. Earth. Planet. Sc. Lett. 351-352, 95-104, DOI: 10.1016/j.epsl.2012.07.008, 2012.

Blaauw, M., Andres Christen, J.: Flexible paleoclimate age-depth models using an autoregressive gamma process. Bayesian. Anal. 6, 457-474, DOI: 10.1214/11-BA618, 2011.

Blaga, C.I., Reichart, G.-J., Heiri, O., Sinninghe Damsté, J.S.: Tetraether membrane lipid distributions in water-column particulate matter and sediments: a study of 47 European lakes along a north–south transect. J. Paleolimnol. 41, 523-540, DOI: 10.1007/s10933-008-9242-2, 2009.

Blaga, C.I., Reichart, G.-J., Lotter, A.F., Anselmetti, F.S., Sinninghe Damsté, J.S.: A TEX_{86} lake record suggests simultaneous shifts in temperature in Central Europe and Greenland during the last deglaciation. Geophys. Res. Lett. 40, 948-953, DOI: 10.1002/grl.50181, 2013.

Blaga, C.I., Reichart, G.-J., Vissers, E.W., Lotter, A.F., Anselmetti, F.S., Sinninghe Damsté, J.S.: Seasonal changes in glycerol dialkyl glycerol tetraether concentrations and fluxes in a perialpine lake: Implications for the use of the TEX86 and BIT proxies. Geochim. Cosmochim. Ac. 75, 6416-6428, DOI: 10.1016/j.gca.2011.08.016, 2011.

Blaga, C.I., Reichart, G.J., Schouten, S., Lotter, A.F., Werne, J.P., Kosten, S., Mazzeo, N., Lacerot, G., Damste, J.S.S.: Branched glycerol dialkyl glycerol tetraethers in lake sediments: Can they be used as temperature and pH proxies? Org. Geochem. 41, 1225-1234, DOI: 10.1016/j.orggeochem.2010.07.002, 2010.

Buckles, L.K., Villanueva, L., Weijers, J.W.H., Verschuren, D., Damsté, J.S.S.: Linking isoprenoidal GDGT membrane lipid distributions with gene abundances of ammonia-oxidizing Thaumarchaeota and uncultured crenarchaeotal groups in the water column of a tropical lake (Lake Challa, East Africa). Environ.l Microbiol. 15, 2445-2462, DOI: 10.1111/1462-2920.12118, 2013.

Carlson, A.E., LeGrande, A.N., Oppo, D.W., Came, R.E., Schmidt, G.A., Anslow, F.S., Licciardi, J.M., Obbink, E.A.: Rapid early Holocene deglaciation of the Laurentide ice sheet. Nature Geosci. 1, 620-624, DOI: 10.1038/ngeo285.

Castañeda, I.S., Schouten, S.: A review of molecular organic proxies for examining modern and ancient lacustrine environments. Quaternary. Sci. Rev. 30, 2851-2891, DOI: 10.1016/j.quascirev.2011.07.009, 2011.

Castañeda, I.S., Schouten, S.: Corrigendum to “A review of molecular organic proxies for examining modern and ancient lacustrine environments” [Quat. Sci. Rev. 30 (2011) 2851–2891]. Quaternary. Sci. Rev. 125, 174-176, DOI: 10.1016/j.quascirev.2015.07.020, 2015.

Cheng, H., Sinha, A., Wang, X., Cruz, F.W., Edwards, R.L.: The Global Paleomonsoon as seen through speleothem records from Asia and the Americas. Clim. Dynam. 39, 1045-1062, DOI: 10.1007/s00382-012-1363-7, 2012.

Contreras-Rosales, L.A., Jennerjahn, T., Tharammal, T., Meyer, V., Lückge, A., Paul, A., Schefuß, E.: Evolution of the Indian Summer Monsoon and terrestrial vegetation in the Bengal region during the past 18 ka. Quaternary. Sci. Rev. 102, 133-148, DOI: 10.1016/j.quascirev.2014.08.010, 2014.

Dang, X., Ding, W., Yang, H., Pancost, R.D., Naafs, B.D.A., Xue, J., Lin, X., Lu, J., Xie, S.: Different temperature dependence of the bacterial brGDGT isomers in 35 Chinese lake sediments compared to that in soils. Org. Geochem., DOI: 10.1016/j.orggeochem.2018.02.008, 2018.

Dang, X.Y., Xue, J.T., Yang, H., Xie, S.C.: Environmental impacts on the distribution of microbial tetraether lipids in Chinese lakes with contrasting pH: Implications for lacustrine paleoenvironmental reconstructions. Sci. China. Earth. Sci. 59, 939-950, DOI: 10.1007/s11430-015-5234-z, 2016.

Dutt, S., Gupta, A.K., Clemens, S.C., Cheng, H., Singh, R.K., Kathayat, G., Edwards, R.L.: Abrupt changes in Indian summer monsoon strength during 33,800 to 5500 years B.P. Geophys. Res. Lett. 42, 5526-5532, DOI: 10.1002/2015GL064015, 2015.

Dykoski, C.A., Edwards, R.L., Cheng, H., Yuan, D., Cai, Y., Zhang, M., Lin, Y., Qing, J., An, Z., Revenaugh, J.: A high-resolution, absolute-dated Holocene and deglacial Asian monsoon record from Dongge Cave, China. Earth. Planet. Sc. Lett. 233, 71-86, DOI: 10.1016/j.epsl.2005.01.036, 2005.

Feng, X., Zhao, C., D'Andrea, W.J., Liang, J., Zhou, A., Shen, J.: Temperature fluctuations during the Common Era in subtropical southwestern China inferred from brGDGTs in a remote alpine lake. Earth. Planet. Sc. Lett. 510, 26-36, DOI: 10.1016/j.epsl.2018.12.028.

Filippi, M.L., Talbot, M.R.: The palaeolimnology of northern Lake Malawi over the last 25 ka based upon the elemental and stable isotopic composition of sedimentary organic matter. Quaternary. Sci. Rev. 24, 1303-1328, DOI: 10.1016/j.quascirev.2004.10.009, 2005.

Gebregiorgis, D., Hathorne, E.C., Sijinkumar, A.V., Nath, B.N., Nürnberg, D., Frank, M.: South Asian summer monsoon variability during the last ~54 kyrs inferred from surface water salinity and river runoff proxies. Quaternary. Sci. Rev. 138, 6-15, DOI: 10.1016/j.quascirev.2016.02.012.

Govil, P., Divakar Naidu, P.: Variations of Indian monsoon precipitation during the last 32 kyr reflected in the surface hydrography of the Western Bay of Bengal. Quaternary. Sci. Rev. 30, 3871-3879, DOI: 10.1016/j.quascirev.2011.10.004, 2011.

Günther, F., Thiele, A., Gleixner, G., Xu, B., Yao, T., Schouten, S.: Distribution of bacterial and archaeal ether lipids in soils and surface sediments of Tibetan lakes: Implications for GDGT-based proxies in saline high mountain lakes. Org. Geochem. 67, 19-30, DOI: 10.1016/j.orggeochem.2013.11.014.

Günther, F., Witt, R., Schouten, S., Mäusbacher, R., Daut, G., Zhu, L., Xu, B., Yao, T., Gleixner, G.: Quaternary ecological responses and impacts of the Indian Ocean Summer Monsoon at Nam Co, Southern Tibetan Plateau. Quaternary. Sci. Rev. 112, 66-77, 10.1016/j.quascirev.2015.01.023.

~~Hopmans, E.C., Weijers, J.W.H., Schefuss, E., Herfort, L., Damste, J.S.S., Schouten, S.: A novel proxy for terrestrial organic matter in sediments based on branched and isoprenoid tetraether lipids. Earth. Planet. Sc. Lett. 224, 107-116, DOI: 10.1016/j.epsl.2004.05.012, 2004~~

Hu, J., Zhou, H., Peng, P.a., Spiro, B.: Seasonal variability in concentrations and fluxes of glycerol dialkyl glycerol tetraethers in Huguangyan Maar Lake, SE China: Implications for the applicability of the MBT-CBT paleotemperature proxy in lacustrine settings. Chem. Geol. 420, 200-212, DOI: 10.1016/j.chemgeo.2015.11.008, 2016.

Kathayat, G., Cheng, H., Sinha, A., Spötl, C., Edwards, R.L., Zhang, H., Li, X., Yi, L., Ning, Y., Cai, Y., Lui, W.L., Breitenbach, S.F.M.: Indian monsoon variability on millennial-orbital timescales. Sci. Rep-UK. 6, DOI: 10.1038/srep24374, 2016.

Kim, J.-G., Jung, M.-Y., Park, S.-J., Rijpstra, W.I.C., Sinninghe Damsté, J.S., Madsen, E.L., Min, D., Kim, J.-S., Kim, G.-J., Rhee, S.-K.: Cultivation of a highly enriched ammonia-oxidizing archaeon of thaumarchaeotal group I.1b from an agricultural soil. Environ. Microbiol. 14, 1528-1543, DOI: 10.1111/j.1462-2920.2012.02740.x, 2012.

Kim, J.-H., van der Meer, J., Schouten, S., Helmke, P., Willmott, V., Sangiorgi, F., Koç, N., Hopmans, E.C., Damsté, J.S.S.: New indices and calibrations derived from the distribution of crenarchaeal isoprenoid tetraether lipids: Implications for past sea surface temperature reconstructions. Geochim. Cosmochim. Ac. 74, 4639-4654, DOI: 10.1016/j.gca.2010.05.027, 2010.

Li, J.J., Pancost, R.D., Naafs, B.D.A., Yang, H., Zhao, C., Xie, S.C.: Distribution of glycerol dialkyl glycerol tetraether (GDGT) lipids in a hypersaline lake system. Org. Geochem. 99, 113-124, DOI: .

Li, J., Pancost, R.D., Naafs, B.D.A., Yang, H., Liu, D., Gong, L., Qiu, X., Xie, S., 2019. Multiple environmental and ecological controls on archaeal ether lipid distributions in saline ponds. Chem. Geol. 529, 119293: DOI: 10.1016/j.chemgeo.2019.119293.

Li, K., Zhou, Y., Zhou, Q., Dong, Y., Zhang, Y., Chang, J., Chen, L., Lu, Y.: Temporal-spatial distribution of euphotic depth and its influencing factors in Lake Chenghai, Yunnan Province, China. J. Lake Sci. 31 (1), 256-267, DOI: 10. 18307 /2019. 0124.

Li, Y., Chen, X., Xiao, X., Zhang, H., Xue, B., Shen, J., Zhang, E.: Diatom-based inference of Asian monsoon precipitation from a volcanic lake in southwest China for the last 18.5 ka. Quaternary. Sci. Rev. 182, 109-120, DOI: 10.1016/j.quascirev.2017.11.021, 2018.

Ling, Y., Sun, Q., Zheng, M., Wang, H., Luo, Y., Dai, X., Xie, M., Zhu, Q.: Alkenone-based temperature and climate reconstruction during the last deglaciation at Lake Dangxiong Co, southwestern Tibetan Plateau. Quatern. Int. 443, 58-69, DOI: 10.1016/j.quaint.2016.07.036.

Ljungqvist, F.C., Krusic, P.J., Sundqvist, H.S., Zorita, E., Brattström, G., Frank, D.: Northern Hemisphere hydroclimate variability over the past twelve centuries. Nature 532, 94-98, DOI: 10.1038/nature17418, 2016.

Lu Z., Study on climatic and environmental changes of the Yunnan Chenghai region recorded bylake sediments since 1800 [D]. Kunming: The master Thesis of Yunnan Normal University, 2018: 39-43.

MARGO Project Members: Constraints on the magnitude and patterns of ocean cooling at the Last Glacial Maximum. Nature Geosci. 2, 127-132, DOI: 10.1038/ngeo411.

McManus, J.F., Francois, R., Gherardi, J.M., Keigwin, L.D., Brown-Leger, S.: Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes. Nature 428, 834-837, DOI: 10.1038/nature02494.

~~Lü, J., Ju, J., Ren, J., Gan, W.: The influence of the Madden-Julian Oscillation activity anomalies on Yunnan's extreme drought of 2009–2010. Sci. China. Earth. Sci. 55, 98-112, DOI: 10.1007/s11430-011-4348-1, 2012.~~

Meegan Kumar, D., Woltering, M., Hopmans, E.C., Sinninghe Damsté, J.S., Schouten, S., Werne, J.P.: The vertical distribution of Thaumarchaeota in the water column of Lake Malawi inferred from core and intact polar tetraether lipids. Org. Geochem. 132, 37-49, DOI: 10.1016/j.orggeochem.2019.03.004, 2019.

~~Nakagawa, T., Kitagawa, H., Yasuda, Y., Tarasov, P.E., Nishida, K., Gotanda, K., Sawai, Y.: Asynchronous Climate Changes in the North Atlantic and Japan During the Last Termination. Science 299, 688-691, DOI: 10.1126/science.1078235, 2003.~~

~~Nakagawa, T., Tarasov, P.E., Kitagawa, H., Yasuda, Y., Gotanda, K.: Seasonally specific responses of the East Asian monsoon to deglacial climate changes. Geology 34, 521-524, DOI: 10.1130/G217641, 2006.~~

Ning, D., Zhang, E., Shulmeister, J., Chang, J., Sun, W., Ni, Z.: Holocene mean annual air temperature (MAAT) reconstruction based on branched glycerol dialkyl glycerol tetraethers from Lake Ximenglongtan, southwestern China. Org. Geochem. 133, 65-76, DOI: 10.1016/j.orggeochem.2019.05.003, 2019.

Pearson, E.J., Juggins, S., Talbot, H.M., Weckstrom, J., Rosen, P., Ryves, D.B., Roberts, S.J., Schmidt, R.: A lacustrine GDGT-temperature calibration from the Scandinavian Arctic to Antarctic: Renewed potential for the application of GDGT-paleothermometry in lakes. Geochim. Cosmochim. Ac. 75, 6225-6238, DOI: 10.1016/j.gca.2011.07.042, 2011.

Pitcher, A., Hopmans, E.C., Mosier, A.C., Park, S.-J., Rhee, S.-K., Francis, C.A., Schouten, S., Sinninghe Damsté, J.S.: Core and Intact Polar Glycerol Dibiphytanyl Glycerol Tetraether Lipids of Ammonia-Oxidizing Archaea Enriched from Marine and Estuarine Sediments. Appl. Environ. Microb. 77, 3468, DOI: 10.1128/AEM.02758-10, 2011.

Powers, L., Werne, J.P., Vanderwoude, A.J., Sinninghe Damsté, J.S., Hopmans, E.C., Schouten, S.: Applicability and calibration of the TEX_{86} paleothermometer in lakes. Org. Geochem. 41, 404-413, DOI: 10.1016/j.orggeochem.2009.11.009, 2010.

Powers, L.A., Werne, J.P., Johnson, T.C., Hopmans, E.C., Damsté, J.S.S., Schouten, S.: Crenarchaeotal membrane lipids in lake sediments: A new paleotemperature proxy for continental paleoclimate reconstruction? Geology 32, 613-616, DOI: 10.1130/G20434.1, 2004.

R Development Core Team, 2013. R: A language and environment for statistical computing, R Foundation for Statistical Computing, Vienna, Austria.

Rashid, H., Flower, B.P., Poore, R.Z., Quinn, T.M.: A ~25 ka Indian Ocean monsoon variability record from the Andaman Sea. Quaternary. Sci. Rev. 26, 2586-2597, DOI: 10.1016/j.quascirev.2007.07.002, 2007.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Ramsey, C.B., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M.: IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55, 1869-1887, DOI: 10.2458/azu_js_rc.55.16947, 2013.

Russell, J.M., Hopmans, E.C., Loomis, S.E., Liang, J., Sinninghe Damsté, J.S.: Distributions of 5- and 6-methyl branched glycerol dialkyl glycerol tetraethers (brGDGTs) in East African lake sediment: Effects of temperature, pH, and new lacustrine paleotemperature calibrations. Org. Geochem. 117, 56-69, DOI: 10.1016/j.orggeochem.2017.12.003, 2018.

Saraswat, R., Lea, D.W., Nigam, R., Mackensen, A., Naik, D.K.: Deglaciation in the tropical Indian Ocean driven by interplay between the regional monsoon and global teleconnections. Earth. Planet. Sc. Lett. 375, 166-175, DOI: 10.1016/j.epsl.2013.05.022, 2013.

Schouten, S., Hopmans, E.C., Schefuß, E., Sinninghe Damsté, J.S.: Distributional variations in marine crenarchaeotal membrane lipids: a new tool for reconstructing ancient sea water temperatures? Earth. Planet. Sc. Lett. 204, 265-274, DOI: 10.1016/S0012-821X(02)00979-2, 2002.

Schouten, S., Hopmans, E.C., Sinninghe Damsté, J.S.: The organic geochemistry of glycerol dialkyl glycerol tetraether lipids: A review. Org. Geochem. 54, 19-61, DOI: 10.1016/j.orggeochem.2012.09.006, 2013.

Schouten, S., Rijpstra, W.I.C., Durisch-Kaiser, E., Schubert, C.J., Sinninghe Damsté, J.S.: Distribution of glycerol dialkyl glycerol tetraether lipids in the water column of Lake Tanganyika. Org. Geochem. 53, 34-37, DOI: 10.1016/j.orggeochem.2012.01.009, 2012.

Shen, C., Liu, K.-b., Tang, L., Overpeck, J.T.: Quantitative relationships between modern pollen rain and climate in the Tibetan Plateau. Rev. Palaeobot. Palyno. 140, 61-77, DOI: 10.1016/j.revpalbo.2006.03.001.

Sinha, A., Kathayat, G., Cheng, H., Breitenbach, S.F.M., Berkelhammer, M., Mudelsee, M., Biswas, J., Edwards, R.L.: Trends and oscillations in the Indian summer monsoon rainfall over the last two millennia. Nat. Commun. 6, DOI:

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10.1038/ncomms7309, 2015.

Sinha, A., Stott, L., Berkelhammer, M., Cheng, H., Edwards, R.L., Buckley, B., Aldenderfer, M., Mudelsee, M.: A global context for megadroughts in monsoon Asia during the past millennium. Quaternary. Sci. Rev. 30, 47-62, DOI: 10.1016/j.quascirev.2010.10.005, 2011.

Sinninghe Damsté, J.S., Ossebaar, J., Abbas, B., Schouten, S., Verschuren, D.: Fluxes and distribution of tetraether lipids in an equatorial African lake: Constraints on the application of the TEX_{86} palaeothermometer and BIT index in lacustrine settings. Geochim. Cosmochim. Ac. 73, 4232-4249, DOI: 10.1016/j.gca.2009.04.022, 2009.

Sinninghe Damsté, J.S., Ossebaar, J., Schouten, S., Verschuren, D.: Distribution of tetraether lipids in the 25-ka sedimentary record of Lake Challa: extracting reliable TEX_{86} and MBT/CBT palaeotemperatures from an equatorial African lake. Quaternary. Sci. Rev. 50, 43-54, DOI: 10.1016/j.quascirev.2012.07.001, 2012a.

Sinninghe Damsté, J.S., Rijpstra, W.I.C., Hopmans, E.C., Jung, M.-Y., Kim, J.-G., Rhee, S.-K., Stieglmeier, M., Schleper, C.: Intact Polar and Core Glycerol Dibiphytanyl Glycerol Tetraether Lipids of Group I.1a and I.1b *Thaumarchaeota* in Soil. Appl. Environ Microb 78, 6866-6874, DOI: 10.1128/AEM.01681-12, 2012b.

~~Stebich, M., Rehfeld, K., Schlütz, F., Tarasov, P.E., Liu, J., Mingram, J.: Holocene vegetation and climate dynamics of NE China based on the pollen record from Sihailongwan Maar Lake. Quaternary. Sci. Rev. 124, 275-289, DOI: 10.1016/j.quascirev.2015.07.021, 2015.~~

~~Sun, Q., Chu, G., Xie, M., Ling, Y., Su, Y., Zhu, Q., Shan, Y., Liu, J.: Long-chain alkenone-inferred temperatures from the last deglaciation to the early Holocene recorded by annually laminated sediments of the maar lake Sihailongwan, northeastern China. Holocene 28, 1173-1180, DOI: 10.1177/0959683618761546, 2018.~~

Sun, W., Zhang, E., Shulmeister, J., Bird, M.I., Chang, J., Shen, J.: Abrupt changes in

Indian summer monsoon strength during the last deglaciation and early Holocene based on stable isotope evidence from Lake Chenghai, southwest China. Quaternary. Sci. Rev. 218, 1-9, DOI: 10.1016/j.quascirev.2019.06.006, 2019.

Tian, L., Wang, M., Zhang, X., Yang, X., Zong, Y., Jia, G., Zheng, Z., Man, M.: Synchronous change of temperature and moisture over the past 50 ka in subtropical southwest China as indicated by biomarker records in a crater lake. Quaternary. Sci. Rev. 212, 121-134, DOI: 10.1016/j.quascirev.2019.04.003, 2019.

Tierney, J.E., Russell, J.M., Huang, Y., Damsté, J.S.S., Hopmans, E.C., Cohen, A.S.: Northern Hemisphere controls on tropical southeast African climate during the past 60,000 years. Science 322, 252-255, DOI: 10.1126/science.1160485, 2008.

Tierney, J.E., Russell, J.M., Eggermont, H., Hopmans, E.C., Verschuren, D., Damste, J.S.S.: Environmental controls on branched tetraether lipid distributions in tropical East African lake sediments. Geochim. Cosmochim. Ac. 74, 4902-4918, DOI: 10.1016/j.gca.2010.06.002, 2010.

Wan, G.J., Chen, J.A., Wu, F.C., Xu, S.Q., Bai, Z.G., Wan, E.Y., Wang, C.S., Huang, R.G., Yeager, K.M., Santschi, P.H.: Coupling between $^{210}Pb_{ex}$ and organic matter in sediments of a nutrient-enriched lake: An example from Lake Chenghai, China. Chem Geol 224, 223-236, DOI: 10.1016/j.chemgeo.2005.07.025, 2005.

Wang, H., Dong, H., Zhang, C.L., Jiang, H., Liu, Z., Zhao, M., Liu, W.: Deglacial and Holocene archaeal lipid-inferred paleohydrology and paleotemperature history of Lake Qinghai, northeastern Qinghai–Tibetan Plateau. Quaternary. Res. 83, 116-126, DOI: 10.1016/j.yqres.2014.10.003, 2015.

Wang, H., Dong, H., Zhang, C.L., Jiang, H., Zhao, M., Liu, Z., Lai, Z., Liu, W.: Water depth affecting thaumarchaeol production in Lake Qinghai, northeastern Qinghai–Tibetan plateau: Implications for paleo lake levels and paleoclimate. Chem. Geol. 368, 76-84, DOI: 10.1016/j.chemgeo.2014.01.009, 2014a.

Wang, H., He, Y., Liu, W., Zhou, A., Kolpakova, M., Krivonogov, S., Liu, Z.: Lake Water Depth Controlling Archaeal Tetraether Distributions in Midlatitude Asia: Implications for Paleo Lake-Level Reconstruction. Geophys. Res. Lett. 46, 5274-5283, DOI: 10.1029/2019GL082157, 2019.

Wang, H., Leng, Q., Liu, W., Yang, H.: A rapid lake-shallowing event terminated preservation of the Miocene Clarkia Fossil Konservat-Lagerstätte (Idaho, USA). Geology 45, 239-242, DOI: 10.1130/G38434.1, 2017a.

Wang, M., Tian, Q., Li, X., Liang, J., He, Y., Hou, J.: TEX_{86} as a potential proxy of lake water pH in the Tibetan Plateau. Palaeogeogr. Palaeocl. 538, 109381, DOI: 10.1016/j.palaeo.2019.109381.

Wang, M., Zheng, Z., Man, M., Hu, J., Gao, Q.: Branched GDGT-based paleotemperature reconstruction of the last 30,000 years in humid monsoon region of Southeast China. Chem. Geol. 463, 94-102, DOI: 10.1016/j.chemgeo.2017.05.014, 2017b.

Wang, Q., Yang, X., Anderson, N.J., Zhang, E., Li, Y.: Diatom response to climate forcing of a deep, alpine lake (Lugu Hu, Yunnan, SW China) during the Last Glacial Maximum and its implications for understanding regional monsoon variability. Quaternary. Sci. Rev. 86, 1-12, DOI: 10.1016/j.quascirev.2013.12.024, 2014b.

Wang, S., Dou, H., 1998. Lakes in China. Science Press, Beijing, China (in Chinese).

Weijers, J.W.H., Schouten, S., Spaargaren, O.C., Damste, J.S.S.: Occurrence and distribution of tetraether membrane lipids in soils: Implications for the use of the TEX_{86} proxy and the BIT index. Org. Geochem. 37, 1680-1693, DOI: 10.1016/j.orggeochem.2006.07.018, 2006.

Wu, D., Chen, X., Lv, F., Brenner, M., Curtis, J., Zhou, A., Chen, J., Abbott, M., Yu, J., Chen, F.: Decoupled early Holocene summer temperature and monsoon precipitation in southwest China. Quaternary. Sci. Rev. 193, 54-67, DOI: 10.1016/j.quascirev.2018.05.038, 2018.

Wu, D., Zhou, A., Chen, X., Yu, J., Zhang, J., Sun, H.: Hydrological and ecosystem response to abrupt changes in the Indian monsoon during the last glacial, as recorded by sediments from Xingyun Lake, Yunnan, China. Palaeogeogr. Palaeocl. 421, 15-23, DOI: 10.1016/j.palaeo.2015.01.005, 2015.

Wu, J., Gagan, M.K., Jiang, X., Xia, W., Wang, S.: Sedimentary geochemical evidence for recent eutrophication of Lake Chenghai, Yunnan, China. J. Paleolimnol. 32, 85-94, 2004.

Yao, Y., Zhao, J., Bauersachs, T., Huang, Y.: Effect of water depth on the TEX_{86} proxy in volcanic lakes of northeastern China. Org. Geochem. 129, 88-98, DOI: 10.1016/j.orggeochem.2019.01.014, 2019.

Yang, H., Xiao, W., Słowakiewicz, M., Ding, W., Ayari, A., Dang, X., Pei, H.: Depth-dependent variation of archaeal ether lipids along soil and peat profiles from southern China: Implications for the use of isoprenoidal GDGTs as environmental tracers. Org. Geochem. 128, 42-56, DOI: https://doi.org/10.1016/j.orggeochem.2018.12.009.

Zhang, E., Chang, J., Cao, Y., Sun, W., Shulmeister, J., Tang, H., Langdon, P.G., Yang, X., Shen, J.: Holocene high-resolution quantitative summer temperature reconstruction based on subfossil chironomids from the southeast margin of the Qinghai-Tibetan Plateau. Quaternary. Sci. Rev. 165, 1-12, DOI: 10.1016/j.quascirev.2017.04.008, 2017a.

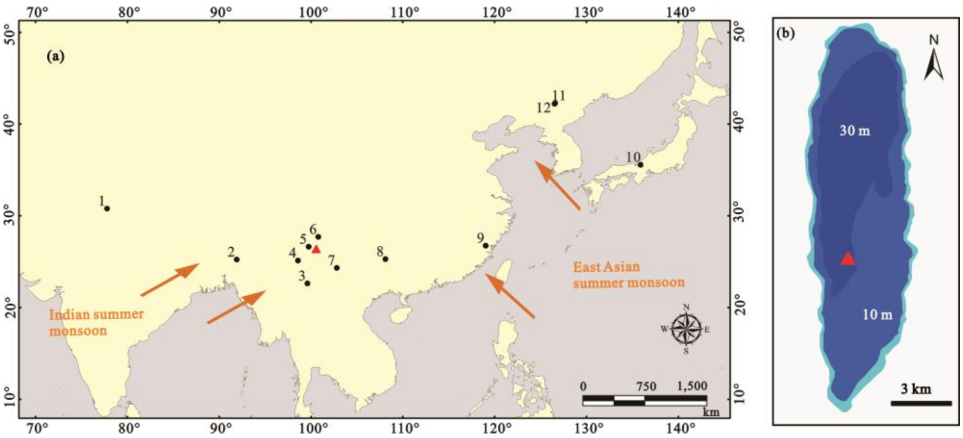
Zhang, E., Chang, J., Shulmeister, J., Langdon, P., Sun, W., Cao, Y., Yang, X., Shen, J.: Summer temperature fluctuations in Southwestern China during the end of the LGM and the last deglaciation. Earth. Planet. Sc. Lett. 509, 78-87, DOI: 10.1016/j.espl.2018.12.024, 2019.

Zhang, E., Sun, W., Chang, J., Ning, D., Shulmeister, J.: Variations of the Indian summer monsoon over the last 30 000 years inferred from a pyrogenic carbon record from south-west China. J. Quaternary. Sci. 33, 131-138, DOI: 10.1002/jqs.3008, 2018.

Zhang, E., Zhao, C., Xue, B., Liu, Z., Yu, Z., Chen, R., Shen, J.: Millennial-scale hydroclimate variations in southwest China linked to tropical Indian Ocean since the Last Glacial Maximum. Geology 45, 435-438, DOI: 10.1130/G38309.1, 2017b.

Zheng, Y., Pancost, R.D., Naafs, B.D.A., Li, Q., Liu, Z., Yang, H.: Transition from a warm and dry to a cold and wet climate in NE China across the Holocene. Earth. Planet. Sc. Lett. 493, 36-46, DOI: 10.1016/j.epsl.2018.04.019, 2018.

Figure captions



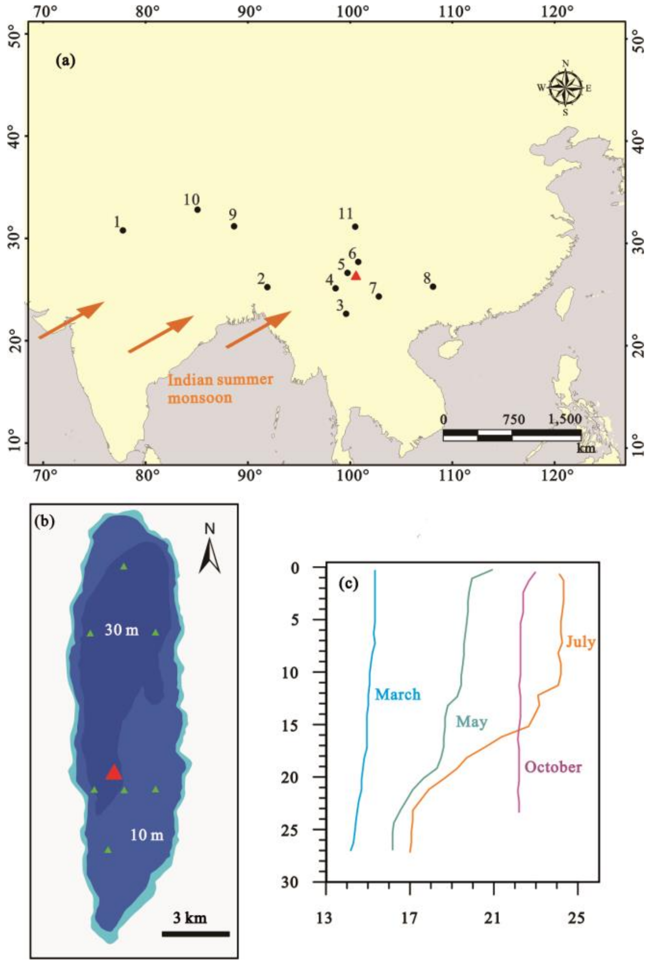


Fig. 1. (a) Map showing the location of Lake Chenghai in southwest China (red triangle) and other sites (circles) mentioned in the text: 1. Bittoo Cave (Kathayat et al., 2016); 2. Mawmluh Cave (Dutt et al., 2015); 3. Lake Ximenglongtan (Ning et al., 2019); 4. Lake Tengchongqinghai (Zhang et al., 2017b; Li et al., 2018; Tian et al., 2019); 5. Lake Tiancai (Zhang et al., 2017a, 2019); 6. Lake Lugu (Wang et al., 2014); 7. Lake Xingyun (Wu et al., 2015, 2018); 8. Dongge Cave (Dykoski et al., 2005); 9. ~~Peat bog Shuizhuyang~~Nam Co (Günther~~Wang~~ et al., ~~2017b~~2015); 10. ~~Lake Suigetsu~~Dangxiong Co (~~Nakagawa~~ Ling et al., 20~~03, 2006~~17); 11. Lake ~~Sihailongwan~~ Yidun (~~Stebich~~ Shen et al., 20~~15; Sun et al., 2018~~06), ~~12. Gushantun peat bog (Zheng et al., 2018). Arrows indicate the dominant atmospheric circulation systems in the region.~~ (b) The red triangle ~~in panel b~~ indicates the location of core CH2016 in Lake Chenghai, while green triangles indicate the locations of surface samples. (c) The vertical variation of Lake Chenghai water temperature in March, May, July and October (Lu, 2018).

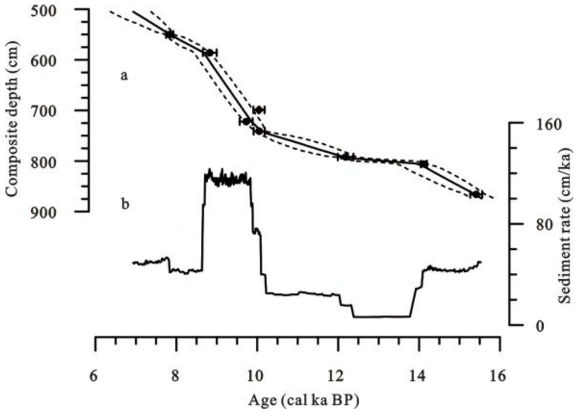
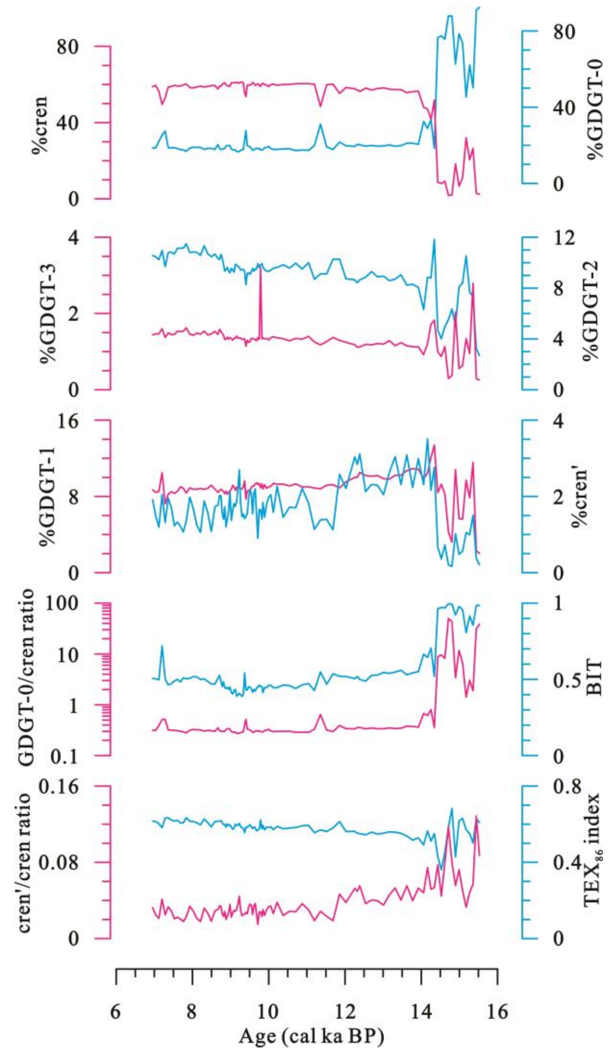


Fig. 2. (a) Age-depth model for the Lake Chenghai sediment core produced ~~by~~ using Bacon software (Blaauw and Andres Christen, 2011~~;~~) from Sun et al.~~,~~ (2019). Dotted lines indicate the 95% confidence range and the solid line indicates the weighted mean ages for each depth, error bars indicate the standard deviation range (2σ) of the calibrated radiocarbon dates. (b) estimated sedimentation rate (Sun et al., 2019).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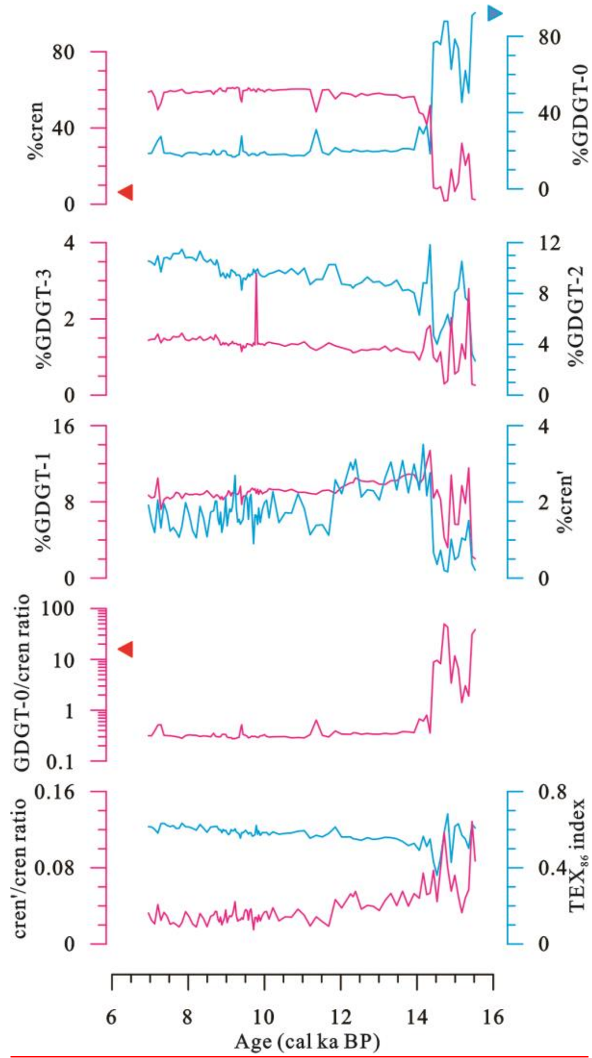

Fig. 3. Variations in the relative isoGDGT distribution and isoGDGTs-based proxies of the Lake Chenghai ~~sediments~~sediment core. The triangles indicate the mean of surface sediments.

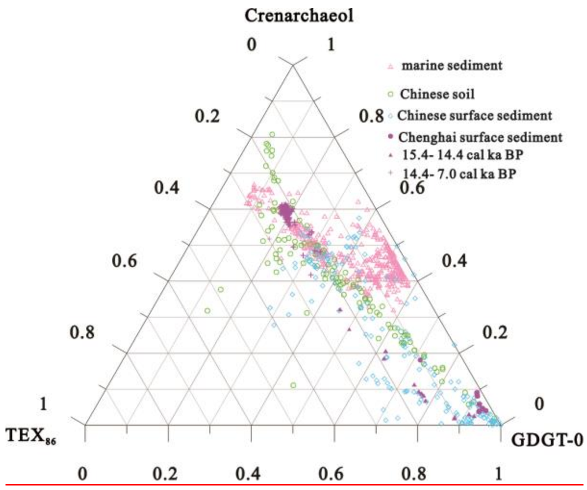

Fig. 4. Ternary diagram showing the distributions of GDGT-0, crenarchaeol, and ‘TEX$_{86}$’ GDGTs in surface and core sediments from Lake Chenghai, global marine sediments (Kim et al., 2010), published Chinese soils compiled by Yao et al. (2019), and lacustrine surface sediments (Günther et al., 2014; Dang et al., 2016; Hu et al., 2016; Li et al., 2016, 2019; Yao et al., 2019; Wang et al., 2020).

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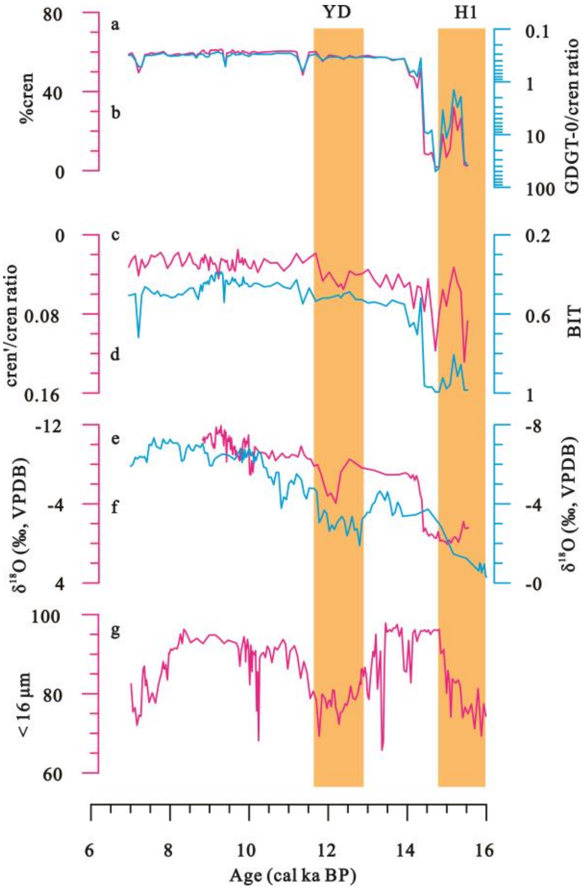
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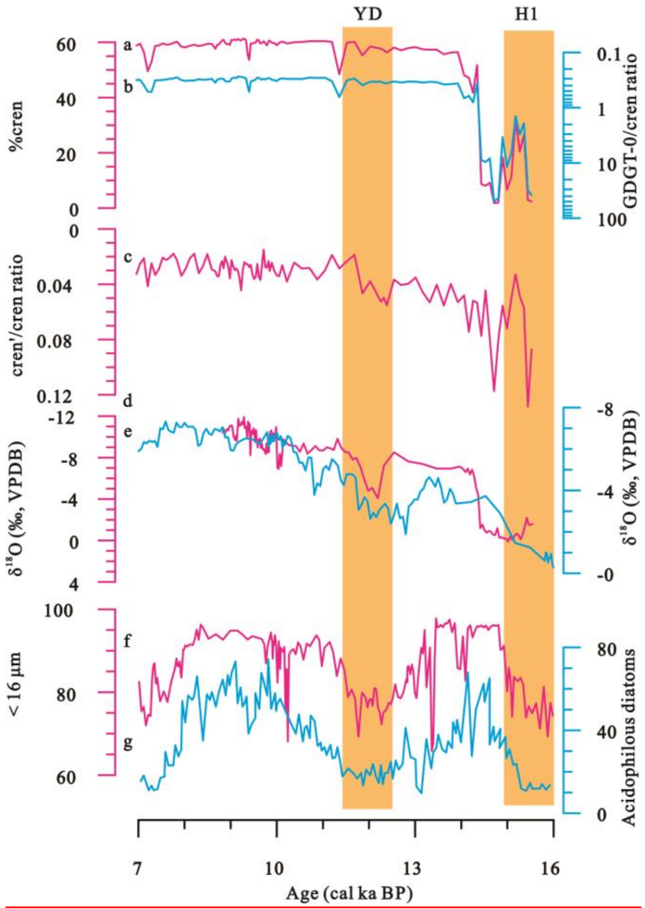
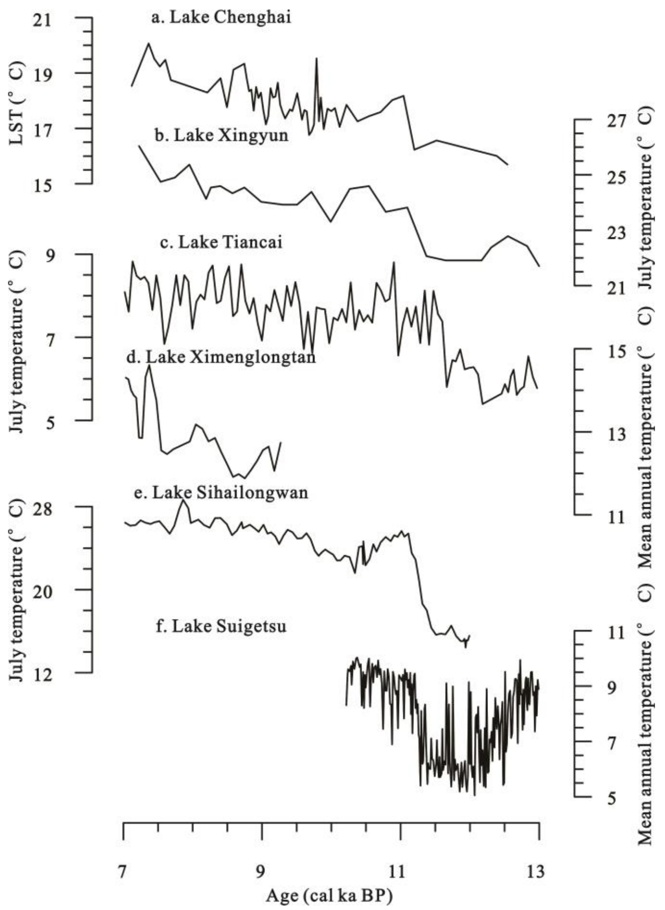


Fig. ~~4~~5. Comparison of the isoGDGT-based lake-level record from Lake Chenghai (a-d) with the $\delta^{18}O$ record of carbonate finer in grain size than 63 μm from Lake Chenghai (e, Sun et al., 2019), the stalagmite $\delta^{18}O$ records from Mawmluh Cave in northeast Indian (f, Dutt et al., 2015); and grain-size record from Lake Tengchongqinghai (g, Zhang et al., 2017). The shading is utilised to represent 'cold' events in the North Atlantic.


a. Lake Chenghai
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15
b. Lake Xingyun
July temperature (° C)
27
25
23
21
c. Lake Tiancai
July temperature (° C)
9
7
5
d. Lake Ximenglongtan
Mean annual temperature (° C)
15
13
11
e. Lake Sihailongwan
July temperature (° C)
28
20
12
f. Lake Suigetsu
Mean annual temperature (° C)
11
9
7
5
7
9
11
13
Age (cal ka BP)

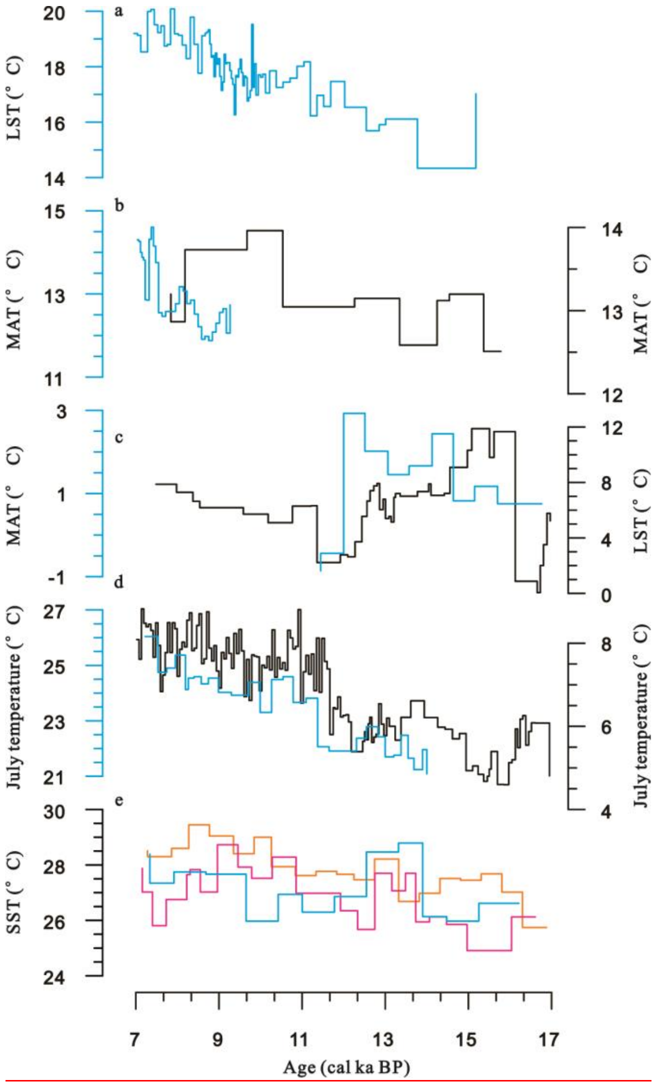

Fig. ~~5~~6. A comparison of TEX$_{86}$-based lake surface temperature of Lake Chenghai (a) with other paleotemperature records. (b) mean annual temperature based on branched GDGTs from Lake Ximenglongtan (blue line, Ning et al., 2019) and Lake Tengchongqinghai (black line, Tian et al., 2019); (c) Alkenone-based mean annual temperature at Lake Dangxiong (blue line, Ling et al., 2017), and TEX$_{86}$-based lake surface temperature of Nam Co from the southern Tibetan Plateau (black line, Günther et al., 2015); (d) July temperature reconstructed from pollen record from Lake Xingyun (~~b,~~blue line, Wu et al., 2018) and subfossil chironomids from Lake Tiancai (~~c,~~black line, Zhang et al., 2017a, 2019);~~ mean annual temperature~~

带格式的：下标

~~reconstructed from Lake Ximenglongtan based on brGDGTs (d, Ning et al., 2019); July temperature reconstructed from pollen record from Lake Sihailongwan (e, Stebich et al., 2015)~~; and (e) sea surface temperatures in the Andaman Sea and Bay of Bengal (Rashid et al., 2007; Govil and Naidu, 2011; Gebregiorgis et al., 2016).~~pollen reconstructed mean annual temperature from Lake Suigetsu (f, Nakagawa et al., 2003).~~