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Climate of the Past
Editors in Chief
Nerilie Abram, Laurie Menviel, Denis-Didier Rousseau and Marit-Solveig Seidenkrantz

Dear Editors in Chief,

Please find enclosed our revised manuscript entitled "*Millennial hydrological variability in the continental northern Neotropics during MIS3-2 inferred from sediments of Lake Petén Itzá, Guatemala*" (Egusphere-2022-787) that we are submitting for your consideration and publication in Climate of the Past. We are utmost grateful for your and the reviewers' comments, suggestions and insightful considerations, which we tried to follow as much as possible and that helped to significantly improve the manuscript.

This revised manuscript contains modifications and corrections according to the suggestions from the anonymous reviewer and Sarah Metcalfe (reviewer #2), as well as comments from Sophie Warken and Rik Tjallingii. The abstract, conclusions and discussion have undergone major modifications in their structure and writing in order to address the questions and comments raised by the reviewers. Specifically, we now provided a data comparison with parallel Site PI-6, which has been studied previously and the benefits of having a higher sedimentation rate and therefore higher resolution at Site PI-2 in the identification of the previously undescribed Greenland Stadials (GS) and Greenland Interstadials (GI) were put in focus. Following the reviewers' suggestions, we also broaden our discussion and now highlight the role of the Caribbean Low-Level Jet and the North American Monsoon in regional moisture input and runoff variability around Petén Itzá, providing a broader discussion around the climatic mechanisms of the region that has previously been focused on the Intertropical Convergence Zone (ITCZ) and the Atlantic Meridional Overturning Circulation (AMOC). Detailed point-by-point changes in response to the reviewers' comments are provided on the following pages.

We hope that you find the revised version suitable for publication in Climate of the Past and are looking forward to hearing from you.

Sincerely,

Rodrigo Martinez-Abarca

REVIEWS

REVIEWER #1

1. The manuscript by Martinez-Abarca et al. presents a detailed reconstruction of Lake Peten Itza's paleoclimate during the MIS3-MIS2 interval at the millennial scale. Certainly, the core PI2 is invaluable in terms of its preservation and high resolution. The manuscript is very high quality in terms of the methods, organization and presentation of the results, which are clearly and well described. The discussion shows a broad and complete comparison with neighbouring records. However, **in the conclusion, the manuscript would benefit a greater audience, if the authors included specific sentences highlighting their particular contribution to the "state of the art" and the understanding of the regional paleoclimate. In other words, what specifically do they "teach us" for the region with this effort?**

> We appreciate the comments made by the anonymous reviewer. We agree with the need to improve the conclusions to make the manuscript more interesting for a greater audience. Thanks to all the comments made by the reviewers, we have included in the conclusions points such as: 1) the hydrological response of Petén Itzá to the changes during MIS3-2, periods that only very few lacustrine records in the northern Neotropics have studied in detail; 2) the climatic forcing mechanisms providing humidity that could increase the runoff in the basin, and mostly associated with the Intertropical Convergence Zone and the Atlantic Meridional Oceanic Circulation in previous studies. In this work we also associate the runoff in Petén Itzá with mechanisms such as the Caribbean Low-Level Jet (CLLJ) and the North American Monsoon, both with little knowledge of their development in the last 60,000 years in the region. We include a wide discussion about the similitude of our runoff proxy with the difference in the sea-surface temperature between the Eastern Pacific and Caribbean, which directly modifies the strength of the CLLJ; 3) the characteristic changes in evaporation/runoff in Petén Itzá related to GS and GI as well as the behavior of these millennial oscillations taking advantage of the high resolution of the PI-2 record, and therefore hitherto not observed by previous studies in the parallel site PI-6; 4) the comparison of our data in site PI-2 with those previously published in site PI-6 to observe differences and similitudes among the sites confirming Petén Itzá as a record of global importance for the study of the paleoclimate of the past 60,000 years.

2. Lines 20-23. References to support the first two sentences are needed.

> References were now added, including
>
> Heinrich, 1988; Lisiecki and Stern, 2016; Bradley and Diaz, 2021

3. Lines 46-47. The sentence that starts with "Moreover, stable isotope geochemistry..." is difficult to understand and needs clarification.

We tried to simply the sentence and now replaced it by the following iteration: “Moreover, stable carbon isotope data in ostracod shells revealed low lake levels during HS associated with dry conditions that may increase the oxygen concentrations in the bottom (Escobar et al., 2012).” (now lines 73-75)

In addition, we have included more specific information about HS1 to expand the state of the art of what is known on Petén Itzá and the effect of cooling periods on the lake.

4. Line 51. The phrase "This body of work" is not clear. What does it mean?

   We have replaced “This body of work” by “previous studies”.

5. Line 53-54. The final sentence of the paragraph is too long and confusing that needs clarification.

   We have separated the sentence and simplified the content to make it easier to comprehend (now lines 60-62).

6. Line 57. The word "mainly" should be deleted.

   The paragraph was modified completely. We tried to avoid the use of the word “mainly”

7. Figure 5. The map lacks all the Caribbean islands, even "Puerto Rico" mentioned in the text. Furthermore, other relevant paleoclimatic records are mentioned in the main text to the study area. **Please include them in the map and the figure caption list**.

   We have included them.

8. In section 5.2 "Millennial-scale climate..." Is **there a reason to favor the nomenclature established in the GICC05 ice-core Greenland record for the stadial and interstadial events (i.e., GS and GI) rather than the so-called Dansgaard/Oeschger events (i.e., D/O)**?

   A Dansgaard-Oeschger event is composed of a GS followed by a GI. We have favored the use of GS and GI because they are recognizable as peaks in our runoff (Titanium) and evaporation (Ca/Ti+Fe) proxies. The GS are represented by high values of Ca/Ti+Fe characteristic of increased evaporation of the lake water, while the GI are represented by low values of Ca/Ti+Fe and high Ti values suggesting more precipitation. We were able to observe that GS 9, 8, 7 and 6 began with an abrupt increase in evaporation and ended with a gradual increase in humidity, while GS 11 and 10 showed an inverse pattern. Discussing these changes in term of D/O would limit our discussion to looking at bundles of events rather than looking at individual dry and humid phases.

REVIEWER #2 SARAH METCALFE

9. This paper presents the record from the PI-2 core from Peten Itza which extends back to 59 cal ka BP. It is compared with the previously published records from core PI-6 taken slightly further to the west. The results are interpreted primarily in terms of changes in the position of the ITCZ and changes in the North Atlantic that are recorded as Greenland Stadials (generally dry here) and Interstadials (generally wetter). Overall, it is noted that the PI-2 record replicates that from PI-6. The paper is generally thorough and well written, but **there isn't really a clear case for why this was worth doing or what, if anything, new was learnt from work on this core which had a higher sedimentation rate than the PI-6 sequence**.

   We appreciate the comments made by the reviewer. We have now modified the introduction, so that - in our opinion - it now is more evident why this research was carried out. We would like to emphasize the following points: (1) we present new geochemical and mineralogical data that complement the interpretations previously made. We show a novel X-ray diffraction dataset that includes quartz, clay minerals and gypsum, which complements the understanding of hydroclimate signal in the sediments; (2) while recent studies tend to investigate older climatic periods (e.g. MIS6) or longer glacial and interglacial oscillations, we focused on MIS3-2 to investigate the hydroclimatic responses in millennial climate oscillations such as GI and GS. Understanding those short-term oscillations will help us to understand the possible environmental response to the current quick global warming; (3) we determine possible climate mechanisms that could have altered moisture transport to the Caribbean region. It was previously suggested that the ITCZ and the intensity of the AMOC were the main mechanisms controlling moisture transport to the Neotropics (Hodell et al. 2008). With our new data, in comparison with other terrestrial and marine records from Mexico, Gulf of Mexico and circum-Caribbean, we propose that the Caribbean Low-Level Jet (CLLJ), moved by the differences in sea-surface temperatures between the Eastern Pacific and the Caribbean, may had an influence on the moisture input into the Petén Itzá region.

   Although the sources of moisture and potential transport mechanisms in this area of study is not trivial, our work provides new hypotheses that can be tested in future work. We have added these suggestions in the revised version in the discussion (see section 5.1.1, for example). Finally, we have added explanations in section 5.2 on the behavior of evaporation and runoff during both GS and GI, respectively. We were able to observe that GS 9, 8, 7 and 6 began with an abrupt increase in evaporation and ended with a gradual increase in runoff, while GS 11 and 10 showed an inverse pattern. This interpretation was only possible because of the high-resolution data that for the first time are reported.

10. The last sentence of the conclusions could, for example, come earlier as this is an **important point about the value of the higher resolution of the sequence.**

   We have emphasized the added value of the PI-2 record in terms of preservation and sedimentation rates (~150 cm ka^{-1}) compared to the PI-6 record (~117 cm ka^{-1}) in the introduction and discussion.

11. The point is made in lines 521-22 about **the confirmation of lake response to hydroclimate across sites, but this is not elaborated on**.

    The structure of the subsections included in part 5.1 of the discussion has been modified. First, we now present our conclusions from Site PI-2, followed by a second paragraph in which we compile the state of the art based on Site PI-6, and whether results are consistent with the Site PI-2 or not and why. Additionally, we include a new figure (Figure 4) that serves as support for the comparison between sites PI-2 and PI-6. We specifically focus on proxies previously publish at site PI-6 such as magnetic susceptibility (indicator of runoff), pollen and charcoal (vegetation changes and paleo-fires), carbon stable isotopes (epilimnion migration), ostracodes taxonomy (conductivity variability) to link them with our results in site PI-2 in terms of runoff, evaporation, redox processes and organic matter sources.

12. The Conclusions make no reference to anything new. **I do recommend that the authors consider making a clearer case for the significance of this paper**. I would have thought that this further record of the high variability of MIS3 was also worthy of more comment (again, somewhat mentioned in passing).

    We have completely revised the conclusions according the original research objectives presented in the introduction. Moreover, we have addressed more widely the discussion around the great hydroclimatic variability of MIS3. Particularly in section 5.1.3.

13. 5.1 is devoted to comparing this Peten Itza sequence with a number of other records across the region. As noted above, the real focus is on the ITCZ, but **there is little recognition that some of the sites used in this comparison are more under the influence of the North American Monsoon than the ITCZ** (it is well established that although the ITCZ and NAM are related, this is not a direct relationship). I think this does matter, as does the greater influence of mid-latitude systems (**potential sources of winter precipitation) at sites such as Babicora and Patzcuaro** (this is mentioned later in lines 446-447). The more westerly sites are also likely to see more influence than the Pacific than the more easterly sites. I just think that the variations across the wider region need more acknowledgement. This also comes in to play in relation to Fig. 5. I found the interpretation of the Babicora record (currently based on Roy et al., 2013) and Patzcuaro (based on Bradbury, 2000) odd, as **there is clear evidence that conditions at both sites were still wetter than present around the LGM.** At Babicora marked shallowing did not apparently occur until around 15 ka and at Patzcuaro wet conditions persisted in to the early Holocene, although the diatom flora changes markedly (a change in moisture source has been suggested). There are other references that could be explored.

    We appreciate the reviewer's comments as we have improved and restructured the discussion as well as regional comparisons with other paleo-records from the Neotropics. We acknowledge the previous absence of discussion regarding the source of moisture from the Pacific or via the North American Monsoon. We have included new literature and studies that provide additional information in this regard. Previous inferences made at Petén Itzá emphasized the role of the

ITCZ and AMOC for paleo-precipitation (see Hodell et al. 2008). We included Figure 6 because, according to studies such as the one by Whyte et al. (2009) or Lachniet et al. (2009), the SST anomalies between the Pacific and the Caribbean may indicate where the moisture is coming from. Our titanium data, when compared to this SST anomaly, shows similar trends in runoff to the lake and thus in moisture. We observed an increase in titanium and thus runoff to Petén Itzá when the Pacific warms, identifying the Pacific as moisture source as a consequence of the intensification of the CLLJ, according to models by Whyte et al. (2009). On the other hand, we have included a short discussion about the influence of the NAM, although little is known about the influence of the NAM during the last 60,000 years. The NAM intensified about 12,000 years ago (Metcalfe et al. 2015), and the Caribbean is currently a source of precipitation during the warmer months (July-August; Hu and Dominguez, 2015). Consequently, we would expect that during warm periods, for example the onset of MIS3, the NAM would be stronger and consequently provide more humidity to Petén Itzá. This has been included in the discussion, however, the Caribbean is a complex region and future studies could help to better discern the effect that this forcing may have exerted on Lake Petén Itzá. The interpretations previously given for the Babicora and Patzcuaro sites have been corrected both in figure 7 and also in the text according with the comments made by Sarah Metcalfe.

14. There seems to be an inconsistency in the text in 5.1.1, which refers to a more northerly location of the ITCZ, then suggests drier summers and more winter rain and then more anoxia due to deeper water**. There is a drier period noted at 55.1 – 53.8 ka. How do you get drier summers if the ITCZ is further north? Is this where the NAM comes in to play?** (although there are suggestions that the monsoon was quite strong, at least during interstadials in MIS3). I think part of the problem here is the interpretation of the Bradbury (1997) paper – thinking has moved on quite a lot since that was published.

    Our general conclusion is that during MIS3 the environment was more humid due to a more northerly position of the ITCZ, in addition to an increase in the intensity of the CLLJ that could contribute to the increase of humidity in Petén Itzá. However, the decrease of Ti between 55.1 and 53.8 cal ka BP coincides with an increase in the ΔSST between the Pacific and the Caribbean causing a weakening of the CLLJ, and possibly altering the runoff response. This discussion can be found in section 5.1.1. The explanation of this particular period in runoff decrease may be associated with a GS that we may have missed due to the uncertainty of our age model in this time interval. However, the presence of a GS would make sense since Desplazes et al. (2013) have proposed a displacement of the ITCZ during the stadials. This has been discussed in section 5.1.2 where the problem of detecting older GS given the age uncertainty is described.

15. The text notes that the lithostratigrahic units of Mueller et al. (2010) are applied here (lines 105-106, 172), but I wondered **whether the application of these units had been tested independently in any way.** There is a suggestion in the Discussion (lines 236-237) that some sort of independent work was done, but this is not explained.

We have now included a sentence at the beginning of the discussion (lines 327-329), explaining that the units were defined by Mueller et al. (2010) based on sedimentological and stratigraphic data. The units have also been verified throughout the basin based on logging data (magnetic susceptibility and density) by Mueller et al. (2010) and Escobar et al. (2012).

16. **I was not convinced that Fig. 7 was in the right place**, it would seem more logical for it to come before the current Fig. 6 which makes the comparisons of millennial change with other records.

    Figure 7 has been removed from the manuscript. Instead, we have added current Figures 5 and 6 because those provide more information about climate mechanisms in the region.

Minor corrections:

17. Line 42 ‘a drop in mean…’
18. Line 253 Missing a few words at the end of the line ‘the end of MIS3 and the start of MIS2’ (as earlier in the text).

We have carried out the first correction. Due to the new structure of the discussion, we have deleted the sentence in line 253.

EXTERNAL COMMENT 1 – SOPHIE WARKEN (received by email)

19. I wanted to let you know that in Figure 4 you plot the data of the Cuban stalagmite, CM, published by Warken et al., 2019 (QSR, https://www.sciencedirect.com/science/article/abs/pii/S0277379118310412), rather than data from Larga cave, Puerto Rico (Warken et al., 2020). But anyway, both datasets should support your interpretation/discussion, especially in Figure 5, I like that very much! If you are also interested to look at temperatures on millennial scale you can also have a look at the speleothem fluid inclusion results which we have published recently also in CP (https://cp.copernicus.org/articles/18/167/2022/).

    We have corrected the references in both figures and throughout the text. In Figure 4, we have corrected the graph, and the caption now refers to both records (Cuba and Larga Cave). Likewise, reference is now made to the reconstructed temperature based on speleothem fluids (Warken et al., 2022).

EXTERNAL COMMENT 2 – RIK TJALLINGII

20. Data should be corrected with a Centred log-ratio (CLR) estimation and a principal component analysis (PCA) should be run to correlate geochemical variables.

    We now normalized the data using the CLR. Figures 3, 4, 5, 6 and 8 were modified accordingly. CLR compositional data express elemental quantities in terms of actual concentrations and incorporate uncertainties acquired during core scanning such as water content, grain size and irregularities of the sediment surface. Our previous interpretations, however, remain unchanged because the trends remain the same. We ran a PCA (see Appendix B).

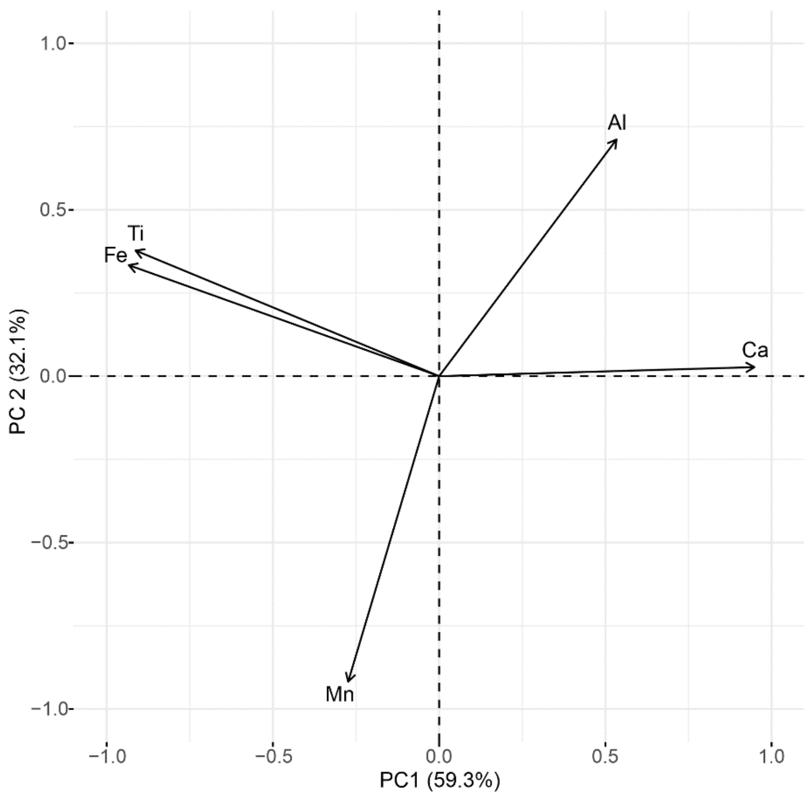

Figure 1. Ranking obtained from the PCA for the geochemical variables measured in the PI-2 record. The ordination analysis is related to changes in runoff and evaporation (PC1) and variations in the oxygen content in the water bottom (PC2).