Author response to Anonymous Referee #3

Article ID: cp-2021-137

General comments:

This is an interesting case study dealing with the reconstruction of paleoclimatic change in arid Central Asia (ACA) over the past millennium, based on a new lacustrine archive from Lake Dalongchi (Tien Shan). The main objective of this study is to decipher the respective contributions of internal and external driving mechanisms of hydroclimatic variability in ACA, which may help to better understand the chain of reactions involved and better constrain future climate model simulations. If the topic is of interest, I find that the manuscript (in its present state) has several flaws, which require some further consideration and development (especially in the Results and Discussion) before it could be accepted for publication. Hence I would recommend major revisions, and I would like to see a revised version of the manuscript before final acceptance.

We would like to thank the reviewer very much for the valuable and constructive comments. We believe that the quality of our manuscript will be substantially improved by these comments and suggestions. Accordingly, we have prepared detailed point-by-point responses below (marked in *blue*). Line numbers and revised figure numbers that refer to the changes in the revised manuscript version have been marked in *red*.

Major comments and concerns:

1. Lines 38-40: Some key references are missing in the state-of-the-art of the Introduction.

See for instance the recent paleolimnological contribution of Rousseau et al., 2020 (https://doi.org/10.1016/j.palaeo.2020.109987) depicting the sequence of glacier fluctuations and associated palaeoclimatic changes over the past millennium in the Tien Shan mountains. See also Zhang et al., 2009; doi: 10.1029/2009gl037375.

Furthermore, other recognized contributions focusing on hydroclimatic changes in ACA during the Holocene are curiously eluded in the Introduction, although they are crucial in understanding the mechanisms at work at decadal to centennial and longer timescales, (e.g., amongst others Mathis et al., 2014; Lauterbach et al., 2014; Huang et al., 2014, Schwarz et al., 2017 and more recently Sorrel et al., 2021).Hence I feel that the introduction lacks, in particular, a concise but general overview focusing on humidity changes in ACA during the Holocene, as a brief introduction of the mechanisms controlling hydroclimate changes in this region. Here, a couple of key references are therefore required in the revised version.

Thank you for the constructive suggestion. we have revised the introduction by adding more records about humidity evolution over the last millennium(Rousseau et al., 2020; Zhang et al., 2003; Zhang et al., 2009; Ma et al., 2008) and an overview of the driving mechanisms during the Holocene (Sorrel et al., 2021; Huang et al., 2014; Schwarz et al., 2017; Mathis et al., 2014; Lauterbach et al., 2014; Chen et al., 2019; Chen et al., 2010; Aichner et al., 2015). (Lines 34-79)

2. Lines 42-43: Can you be more precise and detail what is involved behind the general statement "internal climate variability"? Very imprecise. This is important as you build most of your Discussion on this issue.

Thanks for the comment. The "internal climate variability" refers to the major atmosphere-sea interaction modes. In this paper it mainly refers to the NAO, AMO, or ENSO. We have added some words to the text. (Lines 62-68, 84-85)

3. Lines 60-62: As evaporation clearly predominates on precipitation (rain, snow) and riverine inputs in the annual hydrological budget of Lake Dalongchi, are there available information regarding the groundwater contribution on the hydrological balance (which could be very high in such lacustrine systems)?

Thanks for this comment. As Dalongchi Lake is located in a remote region, and its catchment are very small, there is no detailed information regarding the groundwater contribution. The hydrogeology information in the catchment we can provide is only that the main aquifer is hosted by ophiolitic rocks and categorized as a fissured rock aquifer (http://gis.geoscience.cn/website/hg/viewer.htm). This aquifer has multi-scale hydraulic discontinuities and low groundwater potentiality due to the structural heterogeneities of the ophiolitic rocks (Lods et al., 2020; Jeanpert et al., 2019; Boroninaa et al., 2003). We added this information in lines 94-98. As the groundwater is generally stable, we thought that the groundwater has a negligible impact on the hydrological balance of Lake Dalongchi.

4. Lines 66-67: Do you have more clues about which "shrubs" predominate on the northern slope? Which species precisely?

Yes! During the field work in August 2021, we found that the northern slope is covered by herbs such as Chenopodiaceae, *Artemisia*, Poaceae, and Cyperaceae. We have added it in the manuscript. (Lines 109-110)

5. Line 66: Correct "southern" and "western".

Thanks. We have revised the manuscript accordingly. (Line 109)

6. Line 67: Correct "northern"

Thanks. We have revised the manuscript accordingly. (Line 109)

7. Results, Chronology, lines 107-113: There is no description provided for core lithology. Are they some hiatus identified in the studied core? I see on Figure 2 that part of the core is laminated, while other intervals look more homogeneous. Hence changes in sedimentation rates should be expected over the past millennium. This is of importance because the authors state (in the Abstract, in the Introduction and in the Conclusions, but never in the main part of the text, why not developed any further in the Results?) that their age model has a very high and constant resolution of ca. 1,8 year (!). Hence some more detail regarding lithological change and sedimentation rates should be provided, and developed, in this chapter.

Thanks for the comment. The descriptions for the core lithology were provided in the 3.1 in the original manuscript. In the revised manuscript, we moved the lithology results to 4.1 (Lines 147-161), and added changes in sedimentation rates in Fig. 2. The dramatic lithological variations and the unstable sediment accumulation rates in Unit B well support the fact that the climate is instability during the LIA indicated by HI. We added this in the discussion section. (Lines 230-232)

8. Line 126: "... as has a steep headwall": More detail should be provided in the study site. By the way, we are not provided with any clue regarding the geological setting of the formations surrounding the lake, in particular in the catchment from which most of the inputs originate. Please provide some more emphasis on this.

Thanks for the comment. We have moved it to the "Study site", and revised to "Both the north and south sides of the lake are surrounded by steep mountains". (Lines 100-101)

Regarding to the geological setting, the bedrock in the catchment of Lake Dalongchi is composed of pillow lava, gabbro and limestone blocks included in a matrix of sheared calcareous turbidites. The ophiolitic mélanges are juxtaposed against Paleozoic sedimentary rocks, gneissic granitoids, and andalusite cordierite-bearing micaschist (Xiao et al., 2013; Ma et al., 2006; Gao et al., 1998). We added these in section "Study site" (Lines 91-94)

9. Line 130: There must be a mistake here: the distance between the catchment and the lakeshore should be lower during high stands (compared to low stands). Correct it.

Regarding this question, maybe we have a problem with expression, easy to cause the misunderstanding to others. The distance we mean is the distance between the lakeshore and sampling site rather than between the lakeshore and the catchment. Given that the weak inflows of the runoff into Lake Dalongchi which is a shallow and a small lake with an area only of 1.4 km^2, the distance from the lakeshore to the sampling site is the key to determining the amount of exogenous detrital materials in the core. The detrital materials are easily deposited in the sampling site on the low lake level conditions with a short distance between the sampling site and lakeshore and vice versa. Please see Lines 182-192.

10. Lines 133-134: This statement is not really convincing as one could expect higher riverine inputs (and thus higher magnetic susceptibility or MS, high silt content and higher C/N ratios) during more humid intervals (rather than during dry intervals). What do the pollen say at the local and regional scale? Are there existing and available palynological data, which would favour one of those two hypotheses?

Thanks for the comment. Please see our response to your comment 9. The detrital materials are easily deposited in the sampling site on the low lake level conditions with a short distance between the sampling site and lakeshore and vice versa. Therefore, during the humid/dry period represented by high/low lake level and enlarged/reduced lake area, exogenous materials containing magnetic minerals, coarse grain components, and terrestrial plants were poorly/easily transported to the sampling site. Pollen analysis is a time-consuming work and is still in progress. Our preliminary palynological data from 18 samples in different depths of the core DLC1819 show that a dry climate characterized by herb pollen (~71 %) dominated by *Artemisia*, Chenopodiaceae, and Poaceae during in the MWP, and a wet climate characterized by the rapid increased tree pollen dominated by the Picea (up to 45%) during in the LIA. Please see *the following Figure 1* and in the revised manuscript. (Lines 204-207). Our preliminary palynological result supports the interpretation of multi-proxies in the manuscript, i.e., higher MS, higher silt content and higher C/N ratios reflect more dry climate and vice versa.

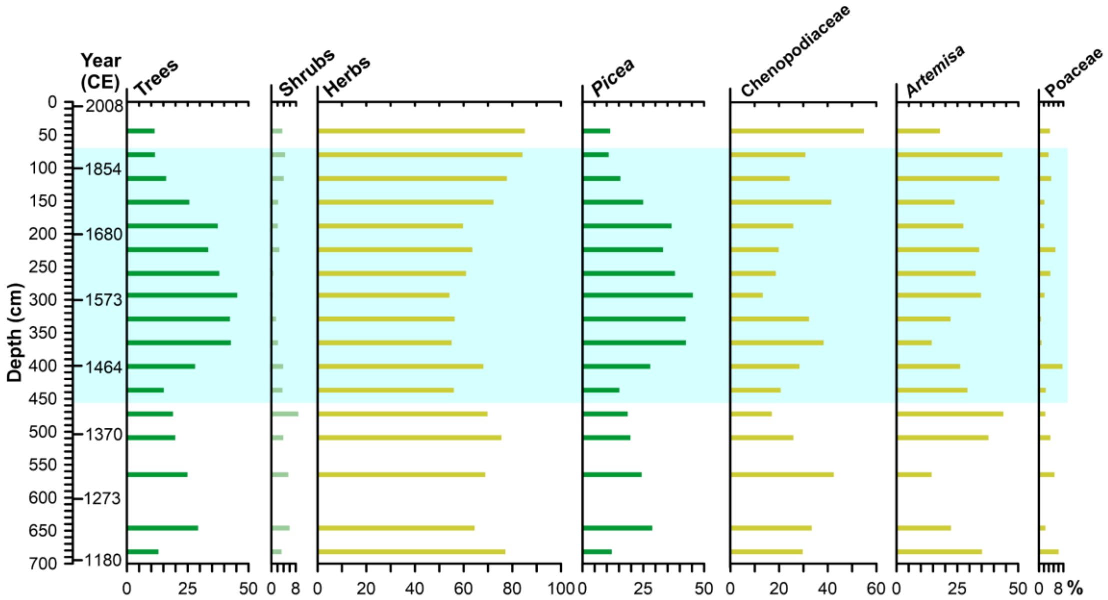

Figure 1. The preliminary results of pollen analysis in DLC1819 core. The light blue rectangle represents the Little Ice Age.

11. Lines 139-140: What is the impact of wind activity around the lake? Is it possible to discriminate between aeolian and riverine inputs in the clastic fraction? Any smear slide analysis performed to check the shape/texture of minerogenic grains? By the way, what is the grain mineralogy of "exogenous materials"? Quartz? Oxides? Else? More information should definitely be provided in this section (and thus also ahead in the Study site section regarding the catchment). Besides, XRF data would have been of help to identify grain size variations, possible sources and discuss changes in clastic inputs over time. Any possibility to add such a dataset in a revised manuscript?

Thanks for your nice suggestions. The prevailing wind is from the northwest and the annual average wind speed is only 2.73 m/s. The average number of sandstorm days is less than 5 days/year based on the meteorological records from 1959 to 1998 (Zhou et al., 2002; Zhang et al., 2021a) (Lines 115-117). In fieldwork, we also found that there is almost no aeolian deposition (no loess and sand desert accumulation) in the basin. So, the wind activity has a little influence on Lake Dalongchi.

According to your insightful suggestion, we randomly selected four samples sifted by 30-mesh and 115-mesh sieve after removing organic matter and carbonates, and observed them under the microscope. We found that the grains in the range of 125-500 μm are characterized by poor roundness with an angular outline which is quite different from the aeolian materials (Zhang et al., 2021b), excluding the possibility that the clastic particles are derived from aeolian deposition in Lake Dalongchi. Please see the *following Figure 2*, Fig. S1 in the supplement, and lines 174-181 in the revised manuscript.

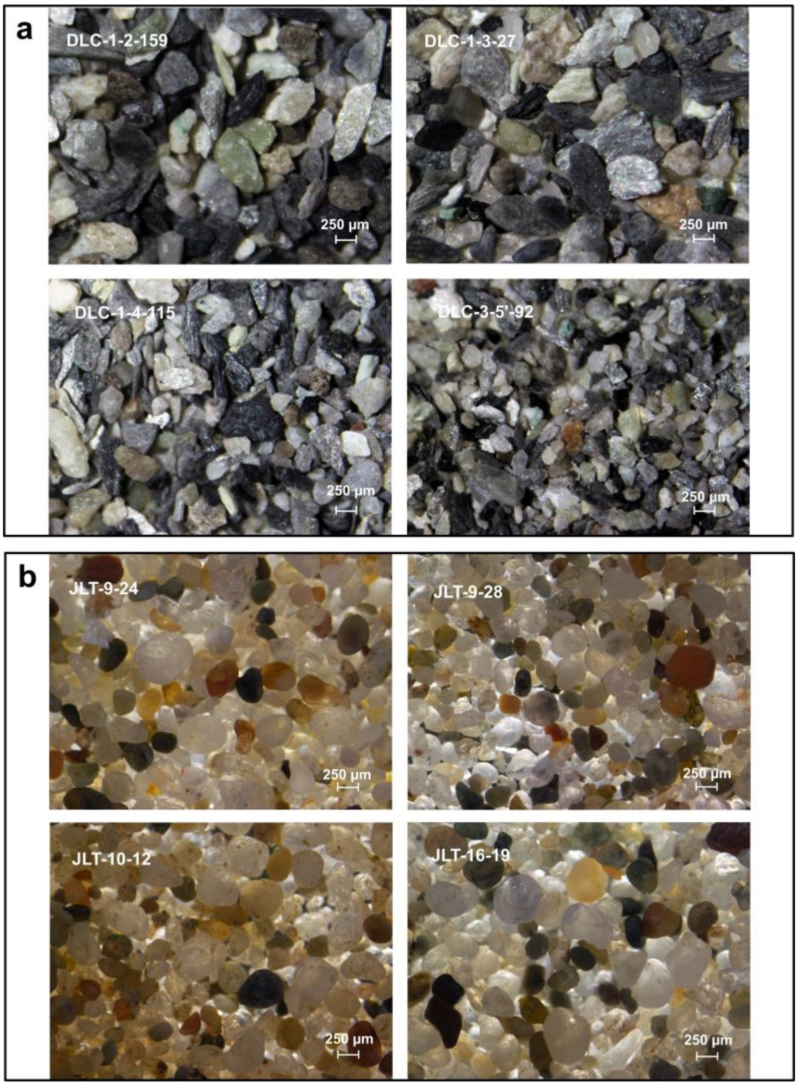

Figure 2. The photomicrograph comparison of 125-500 μm size-fractions in Lake Dalongchi and the typical eolian sand in Jilantai Salt Lake. (a) The 125-500 μm size-fractions from randomly selected samples of DLC1819 core. (b) The typical eolian sand from randomly selected samples of JLT-2010 core (Zhang et al., 2021b).

The grain mineralogy could not distinguish between aeolian and riverine inputs, but we also randomly selected 4 samples in different depths of the core for mineral analysis by X-ray diffraction. The results show that the minerals of Lake Dalongchi sediments are mainly composed of quartz, illite, albite, calcite, and clinochlore (*please see the following Figure 3*). Regarding the XRF analysis, we do not have XRF data at present, but we will do XRF core scanning on a longer core (ca. 15 m) that we plan to get from Lake Dalongchi in September 2022. Thank you much for your suggestion and hope we can get good XRF results in the future.

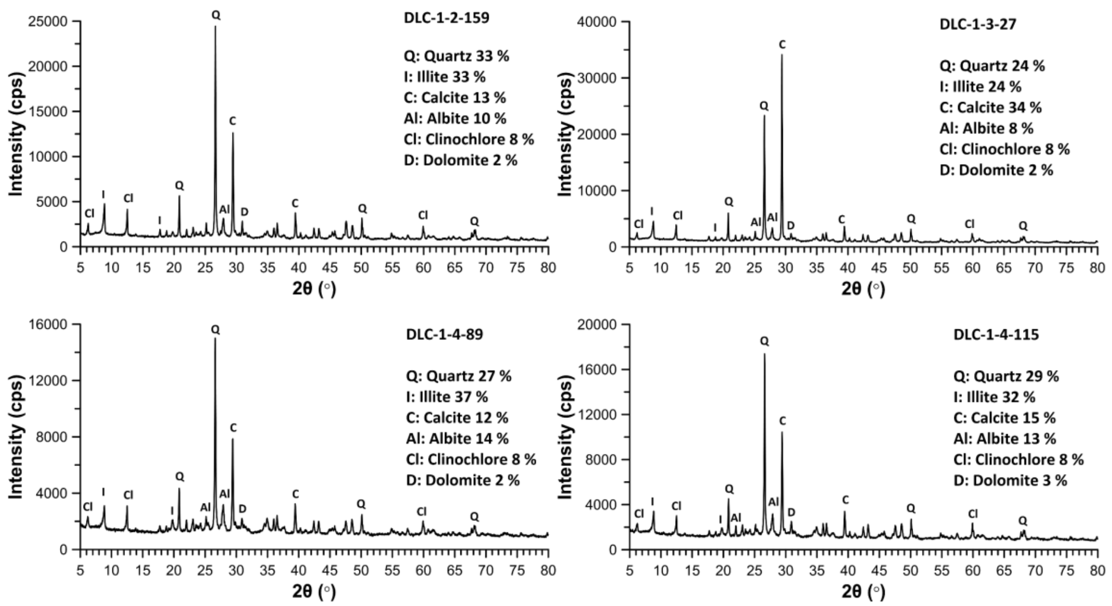

Figure 3. The XRD diffractograms and mineral compositions of 4 randomly selected samples in DLC1819 core

12. Figure 4: Please add the impact of wind processes on the two cartoons, i.e., during High stands and low stands.

Thanks for the comment. The wind activity can be ignored as the the wind speed is low and there no aeolian deposition in catchment of Lake Dalongchi, so we do not consider the wind effect on lake deposition and on the climate reconstruction.

13. Lines 143-145: I doubt that the relationship/consistency between the reconstructed HI and the instrumental relative humidity can be used that straight, since the correlation (as well as the R2; R2=0.298) are rather low. This statement should thus be tempered down.

Thanks for this reminder. We have revised our statement in the manuscript as follows: “There is a generally positive correlation (r = 0.298*) between the reconstructed HI and the instrumental relative humidity records over the past 60 years from the nearby Bayanbuluk meteorological station at the 0.05 significant level, verifying the reliability of the humidity reconstruction.” (Lines 200-202)

14. Lines 145-149: Here the results should be compared with those recently published by Rousseau et al., 2020 (Palaeo3) (https://doi.org/10.1016/j.palaeo. 2020.109987) relying on a proglacial lake from the Tien Shan mountains in Kyrgyzstan over the past millennium. Such a comparison should also be integrated on Fig. 6.

Thank you very much. We have added it to Fig. 6 and revised the discussion in the part of “The humidity changes over the last millennium”. (Lines 214-217, Fig. 6h)

15. Line 161: Replace “during in MWP to LIA” into “between the MWP and the LIA”.

Thanks! We have corrected it. (Line 264)

16. Figure 5: This figure (vs age) is finally very similar to Figure 4 (vs depth). Perhaps you could highlight more clearly (with vertical bands) the most important time slices for the Discussion (driest / humid intervals) on Figure 5.

Thanks for your comment. We have added the humid interval during the LIA indicated by the light grey bars in Fig. 5.

17. Lines 162-166: The authors shortly state the discrepancies between the HI index developed in this study and other humidity records in ACA, but strangely do not provide any reason for it. Then, how would you explain such discrepancies between the different ACA records? We are in the Discussion; hence this should at least be developed a minima (and I would not expect the respective age models to account for the differences observed). Very important.

Thanks for the comment. On the multi-millennial, the hydroclimate changes revealed by our reconstruction are generally in agreement with the hydroclimatic patterns revealed by recent numerous studies in ACA (Chen et al., 2006; Song et al., 2015; Lan et al., 2018; Lan et al., 2019; Zhao et al., 2009; He et al., 2013; Ma and Edmunds, 2006; Gates et al., 2008; Rousseau et al., 2020). (Lines 207-219)
The previous study shows that the higher anomalous climatic instability during the LIA compared to the MWP, suggesting the moisture instability prefers to occur within the conditions of an overall cold climate (Chen et al., 2019b). However, it is not clear how the specific unstable wet and dry climate fluctuated during the LIA, due to the relative low-resolution records in ACA (Chen et al., 2006; Zhao et al., 2009; Lan et al., 2019). The HI reconstruction of Lake Dalongchi provides new evidence for the unstable hydroclimatic variability during the LIA (Fig. 6b). Our high-resolution reconstruction clearly documented several obvious and dramatic secondary humidity fluctuations within the LIA, which are not clearly captured in other current records from ACA (Chen et al., 2006; Ma and Edmunds, 2006; Gates et al., 2008; He et al., 2013) (Fig. 6). The climatic instability during the LIA can also be reflected by the dramatic lithological variations and the unstable sediment accumulation rates in Unit B (Fig. 2) (Lines 220-232)

18. Figure 6: Where is the Badain Jaran locality? Sugan Lake? Lake Gahai? Which country in ACA? This should occur on Figure 1, or on a separate panel in Figure 6.

Thanks! The extent of the ACA (arid Central Asia) is essentially equivalent to the mid-latitude inland region on the western side of the modern Asia summer monsoon. We have annotated the records mentioned in the text in Figure 1 and added the explanation of the ACA. (Lines 700-706, Fig. 1)

19. Line 176: Here it is stated that periodicities of coherence occur from 88 to 146 years, although 88 to 157 years are quoted line 168. Please clarify it.

Thanks! We have revised the “88 to 157 years” to the “~88-146 years”. (Line 233, 275, 278)

20. Lines 188-194: Here again we are in the Discussion, not in the Introduction. This paragraph is in fact almost devoid of any information, as we are only provided with very general statements mentioning that a solar forcing was also involved in other regional records, but without providing any clues regarding the chain of reactions and/or the mechanisms at work behind (at least an attempt could have been done). Such a relationship between solar activity and lake proxies has been long reported in the literature over the past 30 years, but we do not learn much more here. This part of the manuscript would deserve a more in-deep discussion and some more development.

We appreciate the constructive suggestion. The possible physical mechanisms to the hydroclimate changes in ACA of the Solar force are very important. The discussion has been substantially reorganized in the following aspects.

(1) We used the Ensemble empirical mode decomposition (EEMD), a new noise-assisted data analysis (NADA) method (Wu and Huang, 2009; Huang et al., 1998), to extract the century-signal from the original HI series. The results show that there is a firm negative relationship between the century-component of the HI and solar irradiance, which verifies the critical role of the Gleissberg solar cycle in controlling the effective humidity at the century-scale during the last millennium in ACA. (Lines 280-287, Fig. 7f)
(2) We added more discussion regarding several records from ACA that documented the solar fingerprint (Zhao et al., 2009; Yin et al., 2016; Ling et al., 2018; Song et al., 2015). However, rare records in ACA documented the good relationship between the effective humidity changes and the fluctuations of the Gleissberg cycle, even though such records exhibited periodicities of 93 years and 70 to 100 years through the Spectral and wavelet analysis. (Lines 292-298)
(3) Next, we focus on the confusion how solar activity significantly affected hydroclimate fluctuations in ACA over the last millennium. The indirect mechanism is that the solar variability indirectly affects the hydroclimate changes through modulating the NAO state, suggesting solar regulation for hydroclimate might be amplified on a regional scale through atmospheric circulation (Ineson et al., 2011; Shindell et al., 2001; Gray, 2003; Brahim et al., 2018; Kodera, 2002; Yukimoto et al., 2017). However, the direct mechanism of solar forcing through modulating the evaporation seems to have a greater effect on ACA with scare precipitation and intense evaporation. Thus, we preliminarily proposed that solar activity has a direct influence on the effective humidity through controlling regional evaporation in ACA. We further performed the transient experiment forced only by the TSI for

the last millennium using the Max Planck Institute Earth System Model (MPI-ESM) (Jungclaus et al., 2014), to investigate the potential feedback processes between the solar variability and effective humidity at century timescales in ACA. The result also indicates that solar irradiance has an important contribution to the humidity changes of ACA by regulating the temperature and evaporation. (Lines 301-332, Fig. S4 in supplement)

21. Lines 196-219: Same comment here regarding the link between the HI and the ENSO. Even if wavelet analyses suggest a negative relationship between the HI and ENSO, this is however tricky to see any kind of correlation (or anticorrelation) between the two datasets. At least, kind of a correlation could be observed after 1800 AD, but interestingly not before. How would you account for that?

We thank the valuable suggestion. There is a negative phase relationship between the HI and ENSO variance at multidecadal timescales. However, this relationship can only be revealed by the WTC results, rather than the two datasets, because the original HI contains a variety of signals at different timescales. To solve such a problem, we further performed the ensemble empirical mode decomposition (EEMD), a new noise-assisted data analysis method (Huang et al., 1998; Wu and Huang, 2009), to extract the multidecadal signals of the HI. Interestingly, the extracted multidecadal component of the HI exhibits better inverse relationship with the ENSO variance almost throughout the entire time series (please see the *following Figure 4*), which is in line with the WTC results. More discussions were added in the revised manuscript. (Lines 358-377, Fig. 7g and Fig. S3b in the Supplement)

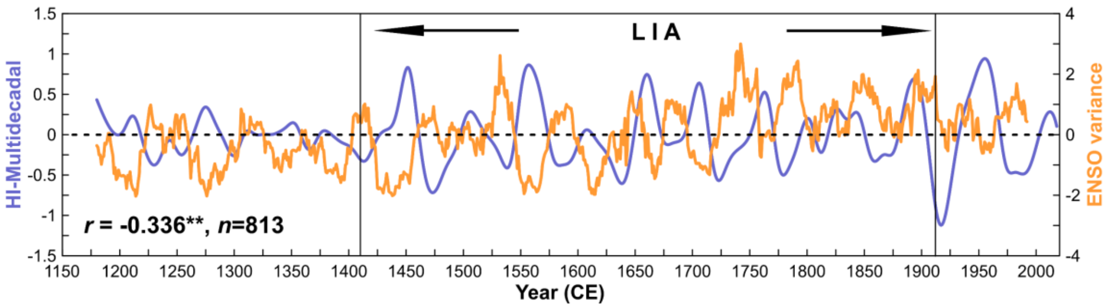

Figure 4. The comparison between the multidecadal component of HI extracted by EEMD and ENSO variance (Li et al., 2011).

22. But, basically, I am puzzled again by the fact that we do not learn much more at the end of the manuscript that what has been widely elsewhere in the literature, especially regarding the driving mechanisms of hydroclimatic variability in ACA during the late Holocene. Hence I would recommend to revise the Discussion by bringing a far stronger case on proxy correlation between the different regional records presented in Figure 6, as when tackling the possible mechanisms at work controlling climate variability over the timespan studied.

Thanks for the comment. Regarding Fig. 6, the comparison among the records can only be on the multi-centennial timescale scales (i.e., WMP, LIA), and this has been discussed by a large number of previous studies. However, there are rarely multidecadal-resolution sediment records in ACA due to the commonly low sedimentation rate and old carbon effect. Therefore, our reconstruction is difficult to compare with other records from ACA at multidecadal to century scales during the last millennium. The purpose of the CWT, WTC and EEMD analysis based on our reconstruction is to reveal the potential mechanisms at different timescales: the dry climate during the MWP and wet climate during the LIA at multi-centennial timescales are mainly attributed to the influence of the NAO and AMO, and the humidity oscillation is directly modulated by the Gleissberg solar cycle at the century-scale and by the quasi-regular period of ENSO at the multidecadal Scale. We also expected more high resolution records to confirm or debate.

Overall, based on your and other two reviews suggestions and comments, we have made substantial revisions by adding EEMD data analysis, sensitivity experiment, and more meaningful previous researches. Four supplementary figures were added in the supplement of the manuscript. Thank you very much for your helpful comments again.

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