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Interactive comment on "Climate impact on the development of Pre-Classic Maya civilization" *by* Kees Nooren et al.

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Reply on "Climate impact on the development of Pre-Classic Maya civilization" (RC-1)

We thank the two reviewers for their constructive comments on our paper "Climate impact on the development of Pre-Classic Maya civilization". We are happy to read that according to the reviewers our two palaeo-precipitation records add valuable new sources of palaeodata for the understanding of human environmental interaction in the Central Maya Lowlands (RC-1 and RC-2).

Hereby we would like to reply on the comments of RC-1.

1. General commentary (RC-1)

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Many of the main comments of RC-1 are related to the structure of the paper:

-The structure of the paper after the methods is quite muddled and difficult to determine a consistent focus. Reorganization of this section with clearly defined results separated from discussion of those results may help.

-I believe many of main points of your discussion are already present in this manuscript, but the structure at present does not bring these points to the forefront.

-Finally, the abrupt ending of the paper left me feeling like this was an incomplete draft.

-Make sure the ideas you highlight at the beginning of the paper (e.g., role of floods in Maya myth, the benefit of having the paired but different size watersheds of the beach ridges and lakes, etc.) are brought up again or emphasized throughout the paper.

We followed RC-1 recommendations and thoroughly restructured paragraph 3 and 4, and added a paragraph with conclusions which will hopefully meet RC-1 expectations.

3. Results

Beach-ridge record

Diatom record lake Tuspan

Wavelet transfer functions

4. Discussion

4.1 Climate change in the CML during the Pre-Classic period

Early Pre-Classic period (1800 – 1000 BCE)

Middle Pre-Classic period (1000 – 400 BCE)

Late Pre-Classic period (400 BCE – 250 CE)

4.2 Precipitation variability

5. Conclusions

For the first time a regional palaeo-precipitation record has been reconstructed for the Central Maya Lowland (CML), based on an exceptionally well dated high resolution beach ridge record. This record indicates centennial scale precipitation fluctuations during the Pre-Classic period that are not always registered in local records, adding valuable new insights into larger scale climatic forcing mechanisms for the CML. The generally poor correlation between the regional and local palaeo-precipitation reconstructions are probably related to spatial precipitation variability, and chronological uncertainties of many records. Additional research of beach ridge formation processes are needed to extend this regional precipitation reconstruction to the Classic and Post-Classic period. We have also generated a local scale palaeo-precipitation record using diatoms preserved in a core from Lake Tuspan, thereby adding an alternative proxy to the relatively high number of local reconstructions predominantly based on oxygen isotope variability. We recognise, however, that diatom preservation is often poor in the carbonate lakes across the wider region. As a result, the correlation between these two reconstructions is variable through time.

Although the occurrence of a prolonged drought during the end of the Early Pre-Classic period, which we report here, is evident in other palaeo-precipitation reconstructions from the CML, the subsequent wet period during the Middle Pre-Classic period, registered in both our new records, is less evident elsewhere. Although many researchers have focused on the impact of drought on the development and disintegration of Maya societies, one should consider this prolonged wet period as potentially unfavourable for

the development and intensification of agriculture in the CML, particularly in the wetter areas. We cannot be certain about the impact of wetter conditions on the Maya. However, owing to the lack of the development at this time we theorise that the wet period could have created poor growing conditions for maize in the CML. In order to test theory, we advocate for the use of process-based modelling approaches which capture heterogeneous environmental constraints on crop growth for given climate boundary conditions such as the approach applied by Dermody et al. (2014).

Our results provide evidence that North Atlantic atmospheric-oceanic forcing plays an important role in the modulation of the observed centennial scale precipitation variability, however further studies are required which compare well-dated terrestrial reconstructions that capture regional signals with solar and oceanic reconstructions to gain a better understanding of climate forcing mechanisms, both in the CML and across the wider region.

Dermody, B.J., van Beek, R.P.H., Meeks, E., Klein Goldewijk, K., Scheidel, W., van der Velde, Y., Bierkens, M.F.P., Wassen, M.J., Dekker, S.C., A virtual water network of the Roman world. Hydrol. Earth Syst. Sci. 18, 5025–5040, 2014.

2. Line by line commentary (RC-1)

71-72: The use of 'likely' twice here reads a little awkward

We agree: the second 'likely' has been removed.

106-111: Can you rephrase this sentence? It is very long and full of multiple clauses.

We agree. Sentence is split into two sentences: Although multiple factors determine the final elevation of the beach ridges, it has been shown that during the period 1775 $\pm$ 95 BCE to 30 $\pm$ 95 CE (at 1Æą), roughly coinciding with the Pre-Classic period, beach ridge elevation has primarily been determined by the discharge of the Usumacinta river. Low elevation anomalies of the beach ridges occur in periods with increased river sediment discharge, which in turn is the product of high precipitation within the

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river catchment.

131: In the methods section, you talk about elemental analysis through X-ray fluorescence and how you use that to identify floods, but in the background on Lake Tuspan, you only discuss diatoms. I was left trying to figure out why you brought up the elemental analysis and whether it was just supporting diatom conclusions or if you were using it as an independent proxy. Perhaps a few sentences in the background clarifying all the techniques you use to make a paleo precip lake signal would help.

We agree. We will give a more thorough description of lake Tuspan's core lithology and XRF results in the Results section. Appendix figure A4 will therefore be moved to the main text. This will likely also accommodate RC-1 request for a more balanced presentation of both records [much of the background (e.g., line 92) emphasizes the beach ridge record and treats the lake as secondary/supplemental data].

152: Missing an extra line spacing. Line spacing added.

167: In the background, you discuss the beach ridges before the lake study, but it's flipped in the methods.

Indeed, we corrected this, and in the discussion section we more consistently discuss the beach ridge record first, followed by the diatom record.

167: It would be nice to have a brief restatement (maybe in the background) on how these ridges were dated rather than having the reader look up cited literature.

We agree. We therefore added the following sentence to the text: The age distance model is based on 35 AMS 14C dated terrestrial macro-remains (mainly leaf fragments isolated from organic debris layers), and 20 OSL dated sand samples (determined on small aliquots of quartz grains) (Nooren et al., 2017b).

223: There is decent evidence of regional drying at the close of the late Preclassic. Does your record support this? Or does it not extend far enough to be confident?

We found a pronounced dry interval during the early part of the Late Pre-Classic Period centred around 275 BCE, but a drought around the close of the late Pre-Classic Period (around 150 – 250 CE), often related to the Pre-Classic collapse, occurred just after the period covered by our beach ridge record (1775 ± 95 BCE to 30 ± 95 CE (at 1Æą)).

233: Long term drying trend in what? Your data? Perhaps describe what you think is the long-term trend of your data, because up to this point it is not clear based on your previous discussion (185-230) that there is a drying trend (it seems quite variable).

We agree. We moved the sentence to the Result section (Diatom record lake Tuspan), and rewrote it as: After relatively high/positive PC-1 values during the Middle and Late Pre-Classic Period we observe a decreasing trend in PC-1 values during the following Classic Period, indicating a gradual increase in lake water salinity. Low PC-1 values between 800 – 950 CE are in accordance with many palaeorecords from the area (Fig. A2) indicating periods of prolonged droughts during the Late Classic Period.

233-239: This whole sections reads more like background information to set up your study rather than discussing your findings. It also feels a bit out of place to discuss broad long term variability AFTER you've covered the short term, period by period results.

We moved this section to paragraph 4.2 (Precipitation variability) of the discussion section. We think that our given explanation of the long term drying trend is more than background information, and should be presented here.

RC-1: The Macal Chasm record shows broad similarities in the timing of long-period dry events with many of the other paleorecords in the region, although this is based on visual matching and not statistical work like wavelet analysis. Why do you think that the Macal Chasm record is the only one to show a match? Some discussion of whether you feel this is due to actual environmental differences or if it is data quality/characteristic driven would be nice here.

We only performed our wavelet analyses between the beach ridge record and all proxy records presented in Fig. A3. Therefore, we are not able to quantitatively compare the Macal Chasm record with other local records. The coherence between the beach ridge record and the Macal-Chasm record may be related to the fact that both records are relatively well dated (as stated in line 251).

RC-1: The Macal Chasm chronology is not particularly precise, especially compared to other stalagmite records in the region like from Yok Balum. The uncertainties in the chronology run 200-400 years in many cases. Even if this doesn't adversely affect your conclusions, you may wish to address this and at the very least qualify how you decided that Macal Chasm is considered 'well-dated'.

We will add 'relatively', and describe the Macal Chasm chronology as relatively well-dated. Although chronological uncertainties of the Macal Chasm record during the Pre-Classic Period are generally in the order of 150 years (at 1 Æą), this is better than most other palaeorecords for this time period. The Yok Balum record encompassed the Classic and Post-Classic period but hardly extend into the Pre-Classic.

269: Why would this period be different? If you are going to tell us that it isn't an analogue, you need to explain why this period is such an aberration.

Good question, we actually don't fully understand how climate forcing mechanisms during the Pre-Classic Period were different from today. We will add after line 271: Probably due a more northerly mean position of the ITCZ during the Pre-Classic period precipitation responded differently to solar forcing then today.

241-281: I feel that this section is one of your weaker parts of the paper. I do not see a convincing argument laid out that the North Atlantic is driving your variations, although I catch a glimpse of it. I would start this section laying out how your record relates with the North Atlantic and atmospheric data and build the argument of what is driving the changes you observe in your data.

We agree that that the centennial scale precipitation variability is likely driven by North Atlantic atmospheric-oceanic forcing forms an important finding of our research. However further research, and the input of climatologists are needed to understand the observed correlation and climate forcing mechanisms. We have added this to the conclusions.

284-305: I also feel that this section is underdeveloped. You are arguing that overly wet conditions may have delayed maize agriculture development, and I think this can be a valid hypothesis. However, you earlier pointed out that climate instability may be to blame for delayed maize (line 76). You also do not supply evidence for your 'overly wet' hypothesis in the form of maize physiology or ethnographic studies. If the region became wetter overall, some low lying areas would be too wet for agriculture, but wouldn't other regions that are presently too dry become potentially productive? Could it simply be a coincidence that local maize varieties hadn't been selected enough for local adaptation until the boom in agricultural clearance you note? Or that populations grew enough in the 'wet' years to support the increased social structures required for large scale agriculture and societal development, rather than maize being actively suppressed by the climate? These alternatives may not be valid, but I don't feel that your argument for wet = bad for maize = suppression of societal development makes enough of a causative case to defend itself against alternative theories. In particular, many have argued that the Classic Period was relatively wetter (e.g., YOK-1, Chicancanab) and this drove societal development and population growth. Others (e.g., Macal Chasm) argued that their data doesn't support a wetter Classic and that other factors, such as climate stability, are more important than wetter vs drier. Where does your research land on this issue? Overall, I think you need to discuss the Maya-environment interactions in much more depth if you wish to make arguments of a somewhat environmentally-deterministic nature.

We are glad that reviewer 1 considers our hypothesis that wet conditions may have delayed the development of maize agriculture a valid hypothesis. However his sugges-

tion for a more in depth discussion of the agricultural and archaeological implications goes beyond the scope of this article, and will need further research, particularly from an archaeological point of view. At this stage we think it is important to point out that one should not only consider prolonged droughts as negative for the development of human societies in the area. We have added in the main text the following: We cannot be certain about the impact of wetter conditions on the Maya. However, owing to the lack of the development at this time we theorise that the wet period could have created poor growing conditions for maize in the CML. In order to test theory, we advocate for the use of process-based modelling approaches which capture heterogeneous environmental constraints on crop growth for given climate boundary conditions such as the approach applied by Dermody et al. (2014).

306: A very abrupt end without any concluding statements. I was left with, "Wait, what was the point or points they really wanted me to focus on?"

A paragraph with conclusions has been added to the text.

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