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Interactive comment on "Spatial and temporal variability of Terminal Classic Period droughts from multiple proxy records on the Yucatan Peninsula, Mexico" *by* Stephanie C. Hunter et al.

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Comments: Hunter et al. compile previously published proxy records and perform statistical tests (namely changepoint analysis) to provide evidence for drying in the Yucatán Peninsula during the TCP. In short, the manuscript provides a background discussion of (i) previously proposed causal forcing mechanisms that may have triggered the TCP droughts, and (ii) the previously published proxy records and their limitations. Subsequently, the manuscript goes on to discuss (i) the link between migration of the ITCZ and TCP droughts, (ii) the spatial and temporal variability of the droughts. The results produced by Hunter et al. show that there are key differences in the special and

temporal drying signatures in the proxy records. Comparison of the data to changepoint analysis conducted on PDO, ENSO and AMO signals led the authors to conclude that the position of the ITCZ was not the sole driver of the TCP droughts. Whereas the idea of a coherent interval of drought across Mesoamerica has been explored in previous studies, the authors describe this manuscript as "novel" in its attempts to "(a) minimize uncertainties inherent to individual proxy records, (b) identify any regional patterns, and (c) explore temporal shifts in drought occurrence during the TCP". However, a large proportion of the theory and analysis presented in the manuscript has been extensively discussed in previously published literature:

Response: First, we would like to thank N. Evans for his very useful comments, and for taking the time to read and comment on our manuscript. In particular, we appreciate the new references that support our findings. Below we address each comment, and outline how we would revise our manuscript to address the concerns raised.

The main concern that Evans raises is that the data analysed in this study have been analysed previously by other authors. Evans questions whether our study is novel, and recommends that we expand on the new contributions made in this study. Indeed, the Terminal Classic Period droughts have been studied by many authors, including those whose proxy records we have analysed in this study. We believe that our research adds new insight into the complexity of the TCP droughts, and brings more detail to the idea of spatial variability in droughts across the Yucatán Peninsula by separating the proxy records into 5 regions (Northwest, West, Central, Northeast, and South). The changepoint analysis used in this study is a novel approach for analyzing proxy records on the Yucatan Peninsula; to our knowledge it has not been used in other proxy studies with multiple types of proxies, although it was used for the analysis of multiple sediment cores in one recent study (Trauth et al., 2018). This method has been used in numerous studies looking at climate and hydroclimate timeseries (references in lines 147-153 of the manuscript), and we wanted to apply this technique to a proxy analysis with multiple types of proxies, which can be difficult to analyse together due to the different mechanisms which affect their formation. Our goal in using this statistical technique was to semi-quantitatively assess if the drought events that occurred during the TCP were in some way different from other dry periods that have been recorded in the proxy records. In our revisions, we will expand upon the motivation behind this study to make these goals more clear.

Three points were raised regarding previously published literature that we will address individually:

1. Comments: Bhattacharya et al. (2017) synthesise regional proxy records to suggest that there is statistically robust evidence of drying between 800 and 1050 CE. By studying control simulations of two general circulation models (GCMs) and the major modes of climate variability (e.g. ENSO, NAO, etc.), the authors also suggest that the pattern of drying may be diagnostic of hydroclimate changes associated with multidecadal variability in the Atlantic Basin. Overall, both the proxy analysis techniques and discussion points are very similar to those utilised by Hunter et al.. Critically, however, Bhattacharya et al. (2017) provide a much more in-depth review of literature proxy age models (using Bayesian age modelling) and causal drought mechanisms (specifically by using GCM control simulations to analyse the processes that produce long-term droughts, including PDO, ENSO and AMO signals). Note that this paper is not cited in the text.

Response: Bhattacharya et al. (2017) synthesized regional proxy records from the Yucatán Peninsula and found evidence of drying between 800 and 1050 CE. The authors suggest that drying is associated with Atlantic multidecadal variability. Bhattacharya et al. (2017) touch on the idea of spatial and temporal variability in the TCP droughts (by noting that some sites show a continuous dry interval from 800 to 1050 CE, while others show several dry intervals). Our study goes into more detail about the spatial variability of droughts on the Yucatán Peninsula by grouping the sites into geographic regions and providing a more in depth comparison between these regions. We also offer a new statistical method for analysing the proxy data, the changepoint analysis,

which helps to identify periods in each time series that have are statistically different conditions compared to the rest of the time series. It should also be noted that our paper focuses solely on drought during the Terminal Classic Period (TCP) rather than the years 0 CE to present as in Bhattacharya et al. (2017). In revising our manuscript, we will include some discussion points related to this paper, and elaborate on how it differs from our study.

2. Comments: Douglas et al. (2016a) provide an in depth review of previous proxy records, and perform z score analysis to highlight any deviation of individual proxy measurements from the mean value of a record. Douglas et al. (2016a) observe two distinct dry intervals, at 770–950 and 1000–1100 CE, separated by an intervening period of relatively wet conditions, as well as spatial variability between records (also see Douglas et al., 2016b).

Response: Indeed, Douglas et al. (2016a) provide an in depth review of many of the same proxy records analysed in this study. A review of the proxy records is included in our manuscript as well, as the mechanisms which allow relation of these proxies to drought conditions are important for the interpretation of these proxy records. The z-score used in Douglas et al. (2016a) looks at deviation of each data point from the mean of the proxy time series, and normalizes all the studied proxy records. While the resampling procedure used helps to estimate drought intensity, we argue that the identification of drought in Douglas et al. (2016a) is still somewhat qualitative- the z-score time series are visually analyzed to identify the periods of drought. As there are natural variations between wet and dry periods in all of the records studied, the intention of our paper is to explore the changepoint method as a means to semi-quantitatively assess which periods of drought were particularly different from other periods. Specifically, were the TCP droughts statistically different from other droughts in the area? We could expand on this in the introduction section of this paper, to help explain our motivation for trying this changepoint methodology on proxy records which have previously been studied. In regards to the spatial variability of droughts, the variability discussed in Douglas et al. (2016a, 2016b) focuses on the difference between the north and south Yucatán, but not the differences within the northern and/or southern regions. This is seen in the division of the z-score analysis into the Northern Yucatán Peninsula and Belize/Central Petén, the comparison of δDwax records from Lake Chichancanab (northern Peninsula) and Lake Salpetén (southern Peninsula), and the comparison between the Chaac (northern Peninsula) and Yok Balum (southern Peninsula) speleothem records. Our study looks at spatial variability in finer detail by splitting the Yucatán Proxy records into Northwest, West, Central, Northeast, and South subgroups. A subtle difference, but an important one because the differences found in our study show that the spatial variability of these droughts was more complex that just a difference between north and south- there were variations from east to west as well, which suggests that local factors may have contributed to the onset of drought in certain areas, while other areas may have experienced no droughts or smaller magnitude droughts. This also supports the conclusion of the manuscript that north-south shifts in the position of the ITCZ weren't the only control on the occurrence of droughts.

3. Comments: Evans et al. (2018) also use Bayesian age modelling and the 'Events' function in R to quantify drought timing in multiple proxy records, and provide a robust method to quantify the drought at Lake Chichancanab, one of the sites highlighted by the authors. This paper is also not cited in the text. Could the authors elaborate as to how their manuscript provides a significant advance to the papers and analysis listed above?

Response: We acknowledge that quantification of drought using the available proxy records is very difficult given the nature of the various proxy types and their relationships to evaporation and precipitation, which is why we chose to take a semi-quantitative approach to this study. This recent paper by Evans et al. (2018) provides an interesting multi-proxy approach to quantifying precipitation at Lake Chichancanab, and we would include a discussion of this paper in the introduction of our manuscript alongside our discussion of Medina-Elizalde et al. (2010), which also attempted to

quantify precipitation during the TCP using speleothem δ18O.

We believe we have discussed in the responses above how our study advances the narrative of TCP droughts; overall, it aims to provide a way to statistically compare the TCP droughts to the climate variability observed in the entire length of the proxy records (the changepoint analysis). It also uses the changepoint analysis to determine if PDO, ENSO, and AMO (all related to the position of the ITCZ) were significantly different at the time of the TCP droughts. Finally, the discussion of spatial variability also notes differences in the timing of droughts from west to east across the Yucatán Peninsula, whereas previous papers have focuses only on the north to south differences.

Comments: Points that would significantly enhance the manuscript:

1. Comments: The use of published age models and the assumption they are accurate (which is highly unlikely) is critical to the subsequent comparison of the data to changepoint analysis conducted on PDO, ENSO and AMO signals. As a bare minimum, Bayesian age analysis should be used to quantify the errors in the age models. Sites with <5 radiocarbon (or other) dates in the last 2000-year interval should not be used (see Bhattacharya et al., 2017).

Response: Upon revising this paper, we could expand on our assessment of the age models by employing Bayesian age analysis to quantify age uncertainty. We agree that sites with fewer than five age dates have much more uncertainty than those with more age dates. We attempted to account for this by ranking each proxy record in terms of confidence in that record. We don't believe it is necessary to completely exclude them from the analysis, as the point of this paper was to look at the available proxy records for the Yucatán Peninsula as a whole. We could, however, make it more clear in our conclusions that these records should not be considered to have definitive evidence of drought.

2. Comments: Each data set used by Hunter et al. spans a different range of calendar dates; thus, the mean values for each data set derive from different time intervals

and may slightly bias interpretations of drought intensity inferred from the changepoint analysis in each record. This should be discussed in addition to Section 4.3, as well as in relation to the 20% uncertainty associated to the changepoint analysis.

Response: We agree. This can be added as part of the discussion about uncertainty in the proxy records, and in particular the ones that have fewer data points during the TCP.

3. Comments: Note that records of gypsum or calcium carbonate concentrations in sediments should be excluded from changepoint analysis: because mineral precipitation occurs at a chemical threshold (on/off) related to the saturation state of gypsum or carbonate minerals, these records are likely not linearly related to the magnitude of reductions in rainfall. Also, these records do not record wet climate intervals, as periods of wetter than average climate do not cause changes in mineral precipitation (Douglas et al., 2016). Additionally, tree rings records should also be excluded as existing records from Mesoamerica generally reflect early spring rainfall, and may reflect a distinct climatic signal from that recorded by speleothem and lake records (Bhattacharya et al., 2017).

Response: The calcium carbonate and magnetic susceptibility (which are both related to gypsum content) records have both been previously published as recorders of Mesoamerican drought (Hodell et al., 1995; Escobar, 2010). They are likely not related to rainfall, but to the ratio of evaporation and precipitation (E/P). Douglas et al. (2016b) also discusses that gypsum and magnetic susceptibility have been used to identify periods of droughts. We have included these records due to their association with E/P and ability to record arid events, not because they are correlated to rainfall or to record wet events. The tree ring record used in this study is a reconstruction of June PDSI (not spring rainfall), and is also not directly located on the Yucatán Peninsula, but to the west of it. While the Barranca de Amealco tree ring record is strongly correlated to April-June precipitation, it was also strongly correlated with June PDSI, and therefore was used as an indicator of Mesoamerican drought. It was included in this

analysis for the purpose of comparison, but as discussed in lines 414-418, this record did not show evidence of TCP droughts (nor was it expected to, which helps to validate the changepoint method used). A discussion of the interpretation of tree ring records in Mesoamerican could be added in revisions to this manuscript, to highlight the fact that they tend to respond to difference climate signals than other proxy types.

4. Comments: The lack of statistical linkage between the analysis of (i) the proxy datasets and (ii) the modes of climate variability means that the assessment is only qualitative. After the points above have been considered, statistical test should be used to quantify the likelihood that PDO, ENSO and AMO signals are forcing drought conditions (see Bhattacharya et al. [2017] for further discussion of mechanistic linkages).

Response: We agree, this analysis would benefit by statistically relating the climate teleconnection signals to the proxy records, and we would add this to our future revision.

5. Comment: A full discussion as to why there is a discrepancy between the Chaac and Yok I speleothems would provide useful insight (building on the explanation of Douglas et al., 2016b), as well as comparison of the statistical techniques used in this manuscript and the paper of Bhattacharya et al. (2017).

Response: We can expand on the discussion of the discrepancies between the Chaac and Yok I speleothems in our revisions. Based on the regional patterns observed in the proxy records, we believe that the discrepancies are recording actual differences in drought timing between these two regions, as 3 out of 5 of the records in the south region appear to have a wet climate during the TCP. This is in contrast to Douglas et al., (2016b), who suggest these differences may be due to evaporation and kinetic isotope effects. We can also include a section outlining how the statistical techniques used in this paper are different from Bhattacharya et al. (2017).

6. Comment: Section 4.3 adds little to the discussion, especially given proxy “uncer-

tainty" is discussed earlier in the text. Indeed, the importance of the proxy dating errors (see above) means that the discussion in this section should be considered prior to statistical analysis.

Response: We agree that perhaps section 4.3 is redundant- we suggest taking important points from Section 4.3 and incorporating them into our earlier discussion of proxy uncertainty, so that all discussion of the uncertainties occur prior to the changepoint analysis.

Comment: Other points to note:

1. Comment: Lines 170-184: Please see the paper by Evans et al. (2018) who used triple oxygen and hydrogen isotopes of gypsum hydration water to provide the a robust, quantitive estimate of precipitation changes during the TCP and deconvolve relative humidity and rainfall.

Response: We note that Evans et al. (2018) conducted work that is relevant to this section, and can add a discussion of these points of the paper to this section.

2. Comment: Lines 185-191: Note that lake level records are sensitive to E-P. In contrast, speleothem records are generally interpreted in terms of the 'amount effect' with isotope ratios covarying with the amount of annual precipitation.

Response: We agree. Lines 185-190 are not discussing speleothem δ18O, but shell δ18O of lake fossils, and this can be clarified. Lines 191-209 discuss speleothem records. We mention the correlation of the Chaac speleothem with precipitation here, as this is the reasoning given in Medina-Elizalde et al. (2010) for interpreting the speleothem as recording variations in precipitation. We can add an explanation of the amount effect here as well to further explain how lake level and speleothem records differ in their interpretation.

3. Comment: Lines 201-203. The largest uncertainty with the record of Medina-Elizalde et al. (2010) is the relatively poor correlation (low rËĘ2 value) in the mod-

ern calibration period, as well as the fact that the magnitude of _18O variability in the Chaac record spans a much wider range than the magnitude of _18O variability from the recent calibration period (see Douglas et al., 2016a).

Response: Lines 201-203 are addressing the assumption of stable temperatures during δ18O proxy formation. However, you make a good point. Perhaps this point is best made in the assessment of individual proxy record uncertainty (the current Section 4.3, but which would be moved before the methods as per your previous suggestion).

4. Comment: A clearer structure in the results section (e.g. segment the proxies by geography) would help the reader.

Response: We organized the results section by site, but we could reorganize and clarify this using subheaders for each of the geographical regions analysed.

5. Comment: The use of qualitative language (e.g. line 364: "a bit less certain"; line 392: "more certain" etc) should be replaced by quantitative results.

Response: We agree. We believe this could be improved upon by including the Bayesian age analysis to help quantify uncertainty in the age models.

References: T. Bhattacharya, J. C. H. Chiang, W. Cheng, Ocean-atmosphere dynamics linked to 800-1050 CE drying in Mesoamerica. Quat. Sci. Rev. 169, 263–277 (2017). P. M. Douglas, A. A. Demarest, M. Brenner, M. A. Canuto, Impacts of climate change on the collapse of lowland Maya civilization. Annu. Rev. Earth Planet. Sci. 44, 613–645 (2016a). P. M. Douglas, M. Brenner, J. H. Curtis, Methods and future directions for paleoclimatology in the Maya lowlands. Global Planet. Change 138, 3–24 (2016b). N. P. Evans, T. K. Bauska, F. Gázquez-Sánchez, M. Brenner, J. H. Curtis, D. A. Hodell, Quantification of drought during the collapse of the classic Maya civilization. Science. 361, 6401, 498-501 (2018). Trauth, M.H., Foerster, V., Junginger, A., Asrat, A., Lamb, H.F., and Schaebitz, F.: Abrupt or gradual? Change 746 point analysis of the late Pleistocene- Holocene climate record from Chew Bahir, Southern Ethiopia, Quaternary

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