Revision notes for cp-2016-137

"*Three distinct Holocene intervals revealed in NW Madagascar: evidence from two stalagmites from two caves, and implications for ITCZ dynamics*"

by Voarintsoa et al.

Acknowledgment:

We thank the CP editor(s) for handling this manuscript.

We thank the reviewers (RC1, SL, and RC2) for their time and efforts at providing comments and suggestions to improve this manuscript.

Summary:

- All suggestions by the two anonymous reviewers (RC1 and RC2) and by Sebastian Luening (SL) have been considered carefully. With these regards, the manuscript has been fully revised (major revisions from our side), but since we were only requested to post our responses at this stage, we made sure to list our responses point by point (as detailed as we can) below.
- Comments from all three reviewers suggest revision of many of our figures, and thus Figures 5, 6, and 7 were revised fully (new figures were also added). Below is the list of changes we made about figures:
    - o Previous figure 1 has not changed
    - o Previous figure 2: we separated the figures so that a new Figure 2 will be showing the age model and a new Figure 3 will be showing the scanned images with the LSW measurements. We did this to make figure presentation better.
    - o Previous figure 3: we separated these figures, so that a new Figure 4 shows the scatterplot and two new Figures 5 and 6 show the stable isotope profiles for the Malagasy Early Holocene Interval (MEHI) and the Malagasy Late Holocene

Interval (MLHI), respectively. Presentation of the time series separately will satisfy all reviewers' concern about Figs. 5 and 6.

  - Previous figure 4: this figure has not changed except the wet/dry/wet to indicate MEHI-MMHI-MLHI. It's number in the revised manuscript is Figure 7
  - Previous figures 5 and 6: These figures have been revised completely, not only to consider the reviewer's suggestions but also to match with the revision in the discussion. We grouped all the possible Holocene forcing (insolation, Temperature, glacier advances and cold periods), pertaining to the ITCZ, into one figure (now Figure 8). The stable isotopes time series were updated earlier.
  - A new Figure 9 has been added to consider the regional comparison, as suggested by RC1, but mainly RC2.
  - Previous figure 7: This figure has also been revised to zoom the 8.2 ka (i.e. an interval between 7800 and 9100 BP). Its number in the revised manuscript is 10.
- We shortened the discussion on ITCZ as suggested by RC2
- Several additions have been made to the revised manuscript:
  - Table 1 is new and it summarizes regional Holocene climate in eastern Africa and surrounding Indian Ocean (as suggested by RC1, but mainly RC2)
  - Figure 9 (as stated above) is new and it is a map showing the position of all locations described in the regional comparison as discussed in the revised manuscript
  - We added a new section revising the climatic setting and the current anomalies in NW Madagascar and surrounding as requested by RC2
  - a very new section discussing ocean oscillation (mainly IOD, but we touched base on ENSO too) was added in response to RC2's request
- We added several figures in the supplementary documents (these figures are not numbered in this revision note, but they will receive actual numbers when the final version of this manuscript is published):
  - Sketches showing how the LSW (Layer-specific width) was measured
  - Three figures showing all the X-Ray Diffraction profiles
  - Figures showing selected (micro)photographs to illustrate some of the interpretation (will be added in the revision)
  - Figure showing SEM image of selected aragonite and calcite layer

  - Figure showing the stable isotope profile (raw and considering correction for isotopic fractionation)
- The list of references has been fully revised in the revised manuscript
- Detailed responses to RC1 are in pages 4-35
- Detailed responses to Sebastian Luening are in pages 35-37
- Detailed responses to RC2 are in pages 37-49

Reviewers' comments are in black.

Authors' responses are in blue.

Please note that all figures in this revision note (Authors' comments, AC) is not numbered (but they are in the revised manuscript). These figures are incorporated next to the describing/corresponding text.

Detailed notes pertaining to reviewers' comments are listed below (point by point) and the changes have been incorporated in the revised manuscript.

Anonymous Referee #1 (RC1):

Received and published: 18 January 2017

Here we provided responses to both the general comments and the specific comments.

This study focuses on speleothems from two caves in Madagascar. Several types of analysis are performed including stable isotopes, laminae, and mineralogy, each of which is anchored using U-Th dates.

Authors' note: The reviewer mentioned "laminae" but we'd like to rectify that we used "layer-specific width" (LSW) and not laminae. This LSW method has been implemented by Sletten et al., 2013 (see their Fig. 2) and Railsback et al., 2014 (see their Fig. 3). LSW is the horizontal distance between two points on the flanks, i.e. points at maximum convexity, of a stalagmite. It is the width that exists near the top of the stalagmite at the time when it was deposited. For a given point, LSW is measured on the growth axis of the stalagmite by determining the horizontal distance across the stalagmite between the points at which the corresponding growth surface becomes tangent to a line inclined 35° to the growth axis. Measurements were done at macroscopically traceable layers and plotted as a function of depth. LSW may vary along the stalagmite's growth axis. Narrow LSW suggests drier conditions and wider LSW suggests wetter conditions.

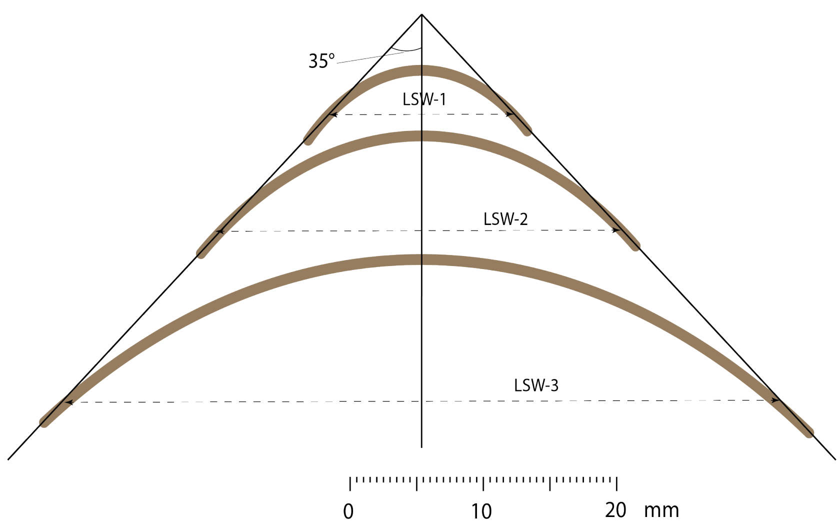

Figure__: Scheme used to determine layer-specific width (this figure will be added in the supplementary section)

The age models appear robust (although an adequate discussion of age determinations and age model calculations is lacking) but there are several problems.

Response: We added a discussion of age determination and age model calculation (please see our response to specific comments below)

First, the time slices spanned by these stalagmites are quite short, being punctuated by long hiatuses. As a result, the larger context of this record is difficult to identify.

Response: It is common that stable isotopes are the fundamental and are the most used proxies in paleoclimate reconstruction. In such circumstances, samples with hiatuses are often disregarded.

We however do not share the same point of view with RC1, who states that "the larger context of this record is difficult to identify" because we believe that the replication of a long-term hiatus (~6.5ka) within the same time interval of the MMHI from two separate caves, 16 km apart, is not an artifact. This long-term hiatus is confirmed by radiometric dating, petrography, and mineralogy. The two stalagmites collected from Anjohibe and Anjokipoty caves, indeed, show roughly three distinct intervals of deposition and non-deposition: (1) between 9.8 and 7.8 ka BP, stalagmites grew (2) between 7.8 and 1.6 ka BP, stalagmites stopped growing, and (3) after 1.6 ka BP, stalagmites resumed to grow. We see this as the big picture, and we based the subdivision of the Malagasy Holocene in accord to these three intervals. With the basic knowledge on how stalagmites form, the timing of stalagmite deposition and the non-deposition from these two distant caves could largely reflect changes in paleohydrology in NW Madagascar, and this could be linked to changes in climate. The larger context of the records could be simplified as follow: the timing of deposition could generally suggest wet conditions that sufficiently recharge the cave's hydrology to feed the stalagmites, whereas the timing of non-deposition suggest dry conditions that inhibited stalagmite deposition.

We addressed this concern by revising several sections in the discussion, we have specifically given more attention to the interpretation of the Malagasy mid-Holocene interval.

Second, I am not convinced of the corrections for differential fractionation between calcite and aragonite d13C values. And associated with this is my concern that there may be microscopically intermingled aragonite and calcite that can only be corrected for isotopically using quantitative XRD, something that was not done here.

Authors' note: we provided responses to general comment here, but also please see specific response to specific comments (page 22-24).

Summary response: Yes, the stalagmites reported in this paper contain both layers of aragonite and layers of calcite as suggested by X-ray diffraction (now we have 15 total XRD profiles from 15 subsamples), microscopic observation of 12 thin sections, and macroscopic observation of the polished surface of the stalagmites. Intermingling between aragonite and calcite at microscopic level exists, but they are not abundant. Because a mixture of aragonite and calcite during sampling could change the stable isotope values in speleothems, I was very careful at extracting sample powders and kept record of the mineralogy each time I drilled a sample. Since the sample size for stable isotopes is very small (1.5 x0.5x0.5 mm), avoiding such mineralogical contamination was possible. To give readers the freedom of interpreting and evaluating the stable isotope data with minimal influence from such correction, we decided to update the stable isotope time series in all the figures of the main manuscript to only show the raw data, and added a separate time series plot in the supplementary document showing both the untransformed and transformed values. We revised the texts in the manuscript accordingly.

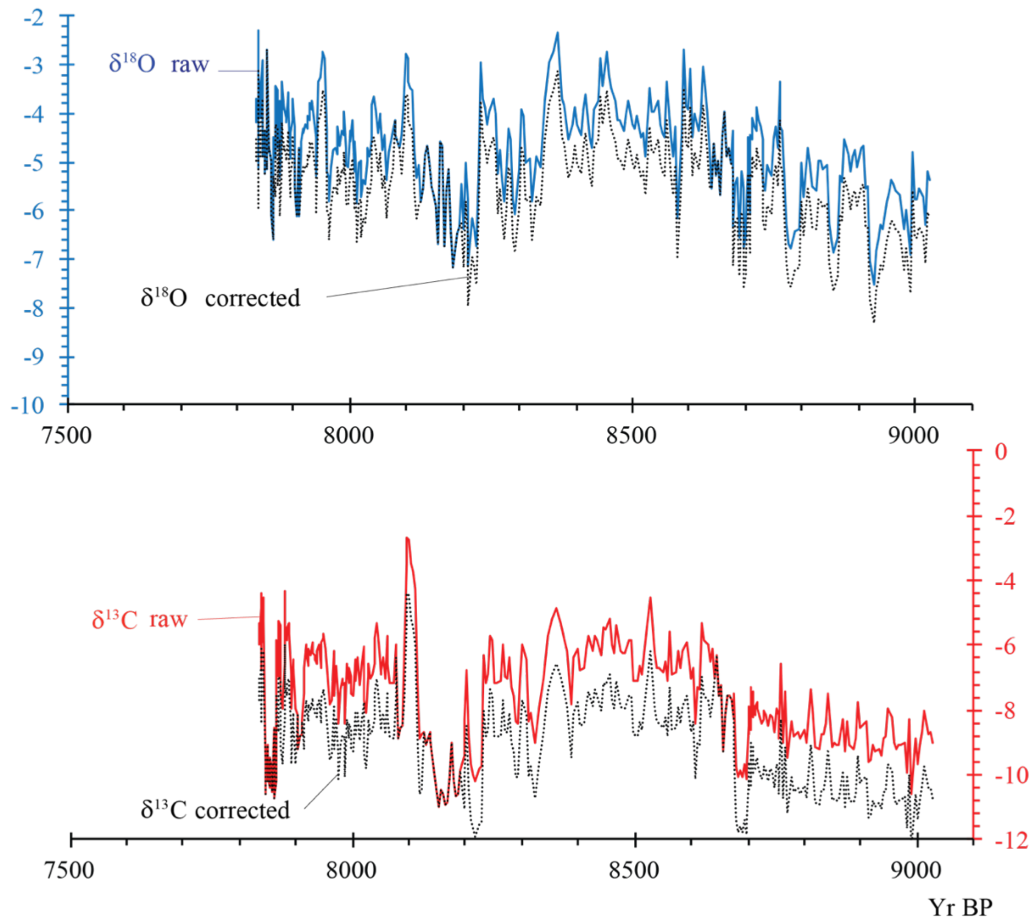

Figure_: Example of the stable isotope of oxygen and carbon profiles showing the raw and corrected values for ANJB-2 during the MEHI.

Detailed response*:*

Literature review of C&O in calcite and aragonite that pertains to reviewer's comments:

The reviewer made a very good point at addressing this aragonite-calcite mixture in stalagmites. Yes, intermingled aragonite-calcite in stalagmite layer could be expected (e.g. Frisia et al., 2002; Gonzalez and Lohmann, 1988; Ortega et al., 2005; Railsback et al., 1994; Woo and Choi, 2006), either as a result of diagenetic processes (e.g. Zhang et al., 2014) or purely primary crystallization of calcite and aragonite when the solution is saturated with these minerals (e.g. Sletten et al., 2013; Railsback et al., 1994). In several aragonite-bearing stalagmite, it is very likely that the aragonite-calcite mixture at microscopic level is expected (e.g. Frisia et al., 2002; Railsback et al., 1994; Lachniet et al., 2012), and this mixture, often variable in proportions (e.g. see Fig. 3 of Sletten et al., 2013; Zhang et al., 2014, Scroxton et al., 2017), could complicate interpretation of stable isotope variations (Frisia et al., 2002; Zhang et al., 2014; McMillan et al., 2005) in a strict paleoclimate context (Fairchild et al., 2006; Lachniet et al., 2012). The complication specifically arises from the different H_2O-$CaCO_3$ equilibrium fractionation factors for aragonite and calcite (e.g. Lachniet, 2009; Rubinson and Clayton, 1969; Romanek et al., 1992; Kim et al., 2007). Investigation of the polished surface of the two stalagmites suggests that the samples did not experience extensive diagenetic alteration, such as the case identified in Zhang et al. (2014) and Lachniet et al. (2012).

We agree that X-ray diffraction is the excellent method to quantify the calcite-aragonite proportion in stalagmite, such as performed by Frisia et al., 2002; Sletten et al., 2013; Zhang et al., 2013; Zhang et al., 2014; Lachniet et al., 2012; Scroxton et al., 2017). We indeed ran ten additional X-ray diffraction analyzes (see figures below, these figures will be added in the supplementary section) on our stalagmites, thus a total of 15 X-ray diffraction analyzes to better resolve the pattern of mineral distribution in our stalagmites. Those X-ray diffraction results agree with our original observation, which was combined with careful microscopic observation of the samples. We specifically looked at twelve oversized thin sections under Leitz Laborlux 12 and under Leica DMLP, equipped with QCapture, to have a thorough understanding of the sample's internal structure, texture, and mineralogy. We have found that the boundary between calcite and aragonite throughout the sample is overall sharp (see figure below). Above all these, we did not find strong evidence of diagenetic alteration.

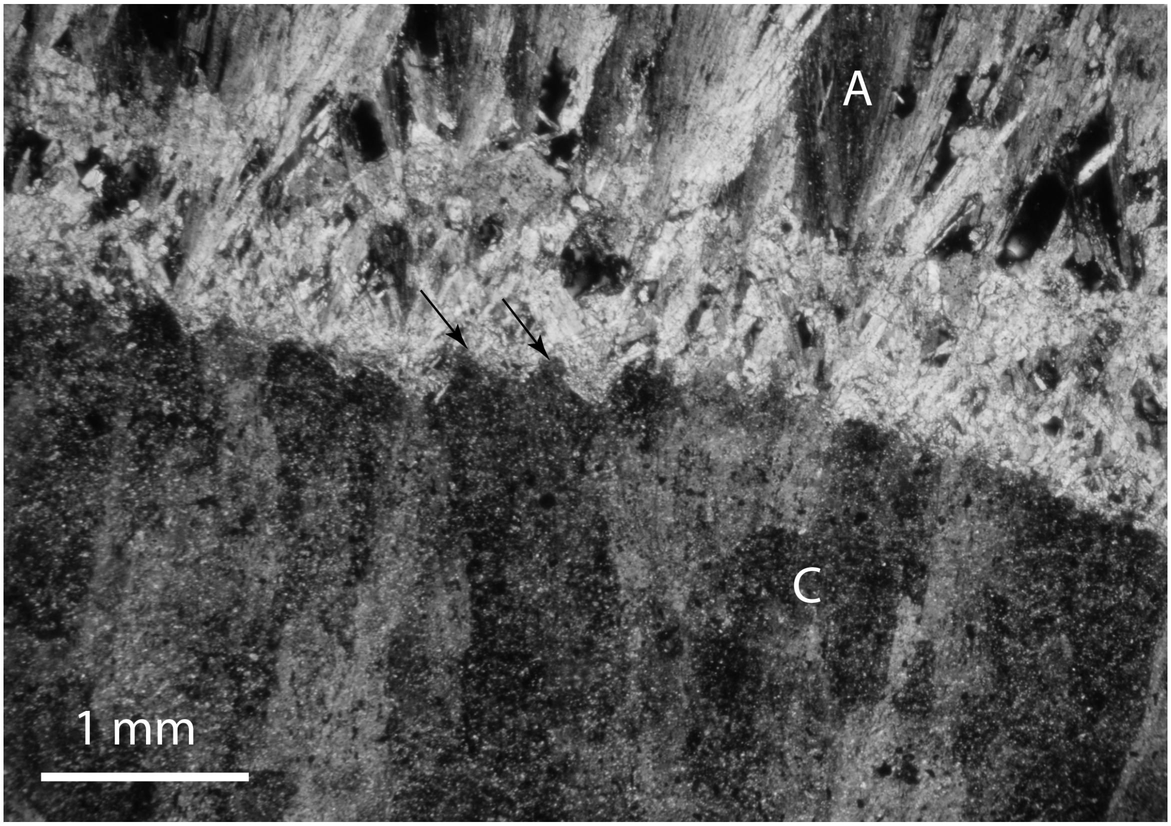

Figure__: Microphotograph showing the sharp boundary between calcite (C) and aragonite (A) in Stalagmite ANJB-2. Indicated with two black arrows (near center of image) are two obvious pyramidal termination of calcite.

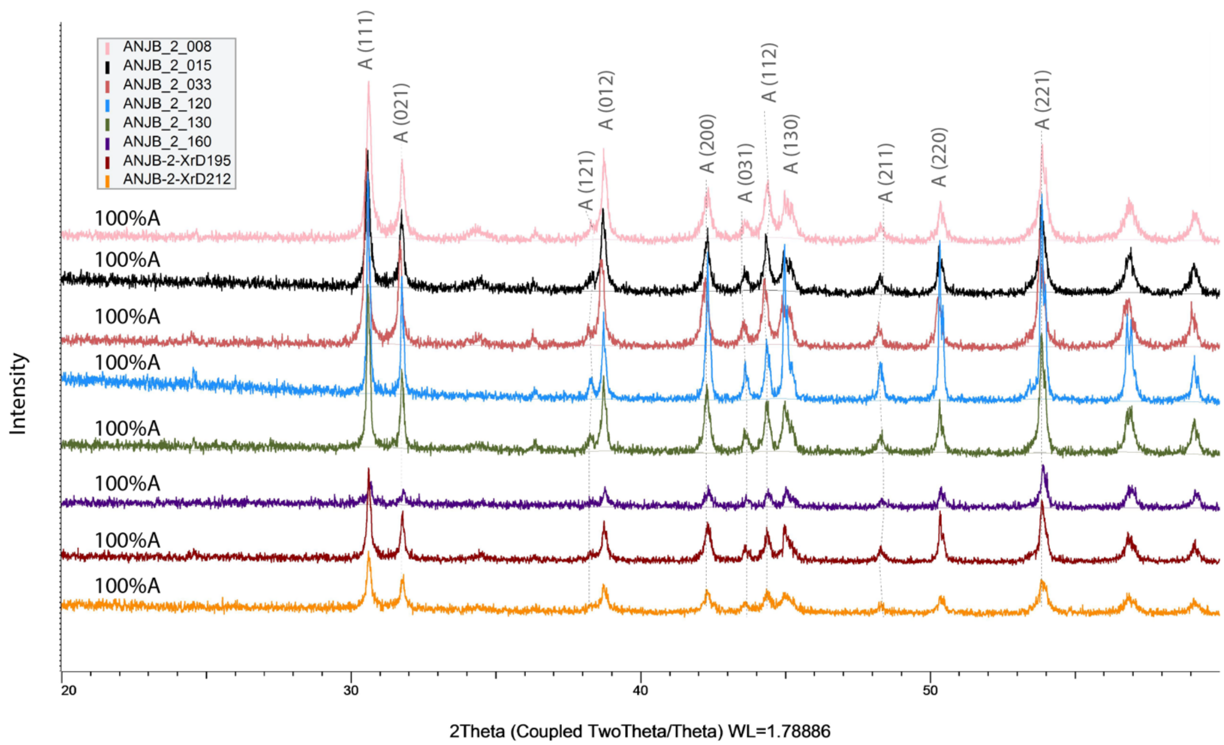

Figure__: XRD profiles of aragonite (A) samples from different locations in Stalagmite ANJB-2. The number in parenthesis are the miller indices of the aragonite mineral.

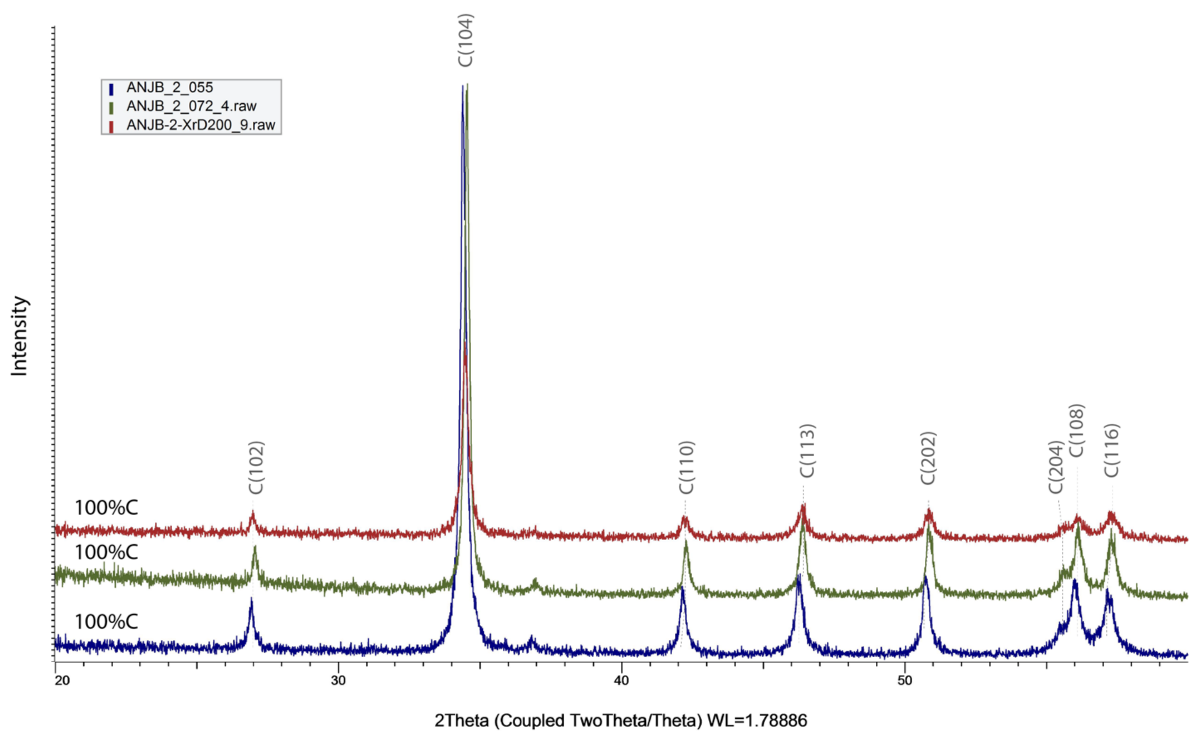

Figure__: XRD profiles of calcite (C) samples from different locations in Stalagmite ANJB-2. The number in parenthesis are the miller indices of the aragonite mineral.

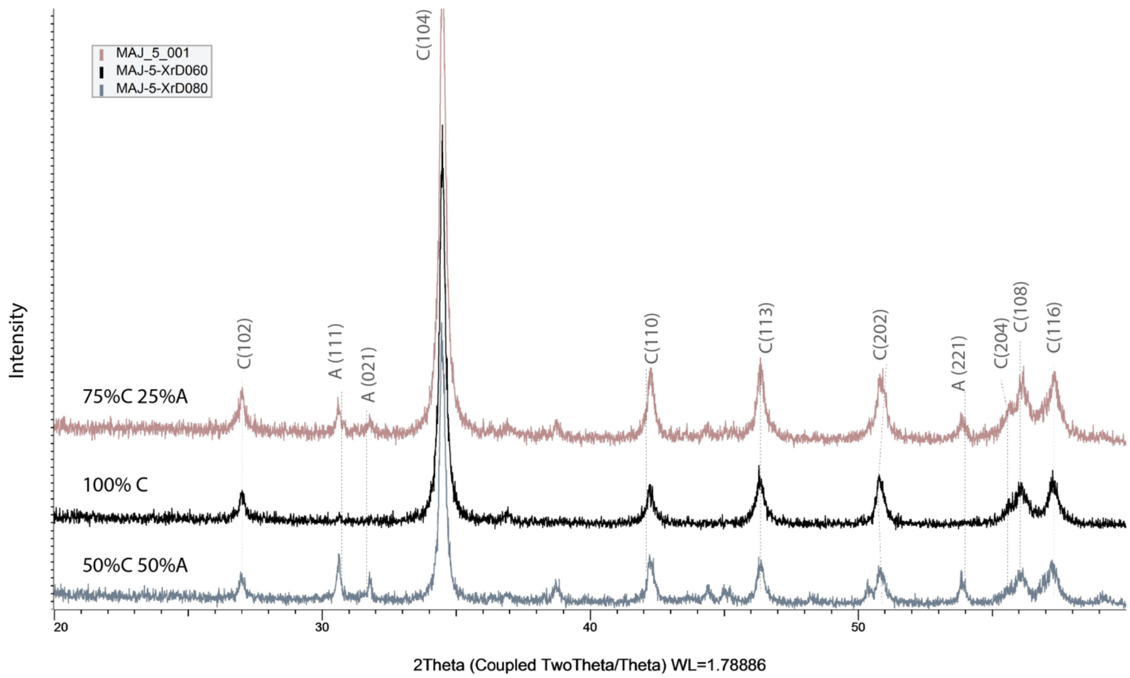

Figure__: XRD profiles of aragonite (A) and calcite (C) samples from different locations in Stalagmite MAJ-5. The number in parenthesis are the miller indices of the mineral. The Aragonite-Calcite mixture in Stalagmite MAJ-5 is due to alternating thin laminae of calcite and aragonite.

Since X-ray diffraction is a specific method dedicated to confirm the spelean mineralogy, the reviewer's suggestions for isotopic correction using X-ray diffraction is wrong. The correct concept about using XRD data in speleothem study is that the mineralogical knowledge from XRD experiments is used to correct raw stable isotope values of primary aragonite to remove the mineralogical bias in isotopic interpretation between calcite and aragonite (e.g. Holmgren et al., 2003; Sletten et al., 2013; Liang et al., 2015; Railsback et al., 2016; Voarintsoa et al., 2017). In addition, the minimum sample weight needed for one X-ray diffraction analysis in our lab is ~30 mg. This value is far greater than the weight of a single stable isotope sample (50-100μg), leading one to question if X-ray diffraction of each stable isotope sample (i.e. trench) is technically feasible.

It is also important to note that the primary stable isotope values are controlled by external factors than solely mineralogical preference to fractionate heavy or light stable isotopes. To elaborate on this, calcium carbonate's $\delta^{13}C$ and $\delta^{18}O$ already inherited the isotopic signals of the sourcing dripwater prior to its precipitation to form stalagmite layers. The dripwater $\delta^{13}C$ and $\delta^{18}O$ could represent the mean stable isotope values of external potential sources of carbon and oxygen.

To summarize, although the stalagmites being studied (ANJB-2 and MAJ-5) contain both calcite and aragonite, the stable isotope corrections (now shown in the supplementary document along with raw stable isotope profile) were performed based on the mineralogy along the stalagmites' growth axis, where stable isotope samples were extracted (I referred to my lab notes since I drilled and ran the samples). Because the sample size is relatively small, potential calcite-aragonite mixture during sampling was avoided (the stable isotopic trenches have recently been verified under binocular), a correction using 1.8 ‰ for $\delta^{13}C$ (Romanek et al., 1992; Rubinson and Clayton, 1969) and using 0.8‰ for $\delta^{18}O$ (Kim and O'Neil, 1997; Tarutani et al., 1969; Kim et al., 2007) sounds appropriate [we revised the text addressing this aragonite-calcite stable isotope fractionation]. We understand that the values used for these corrections are slightly different from experiments to experiments (e.g. Kim and O'Neil, 1997; Tarutani et al., 1969; Grosman and Ku, 1986; Kim et al., 2007; Rubinson and Clayton, 1969; Turner, 1982; Romanek et al., 1992), thus we kept consistent numbers. The detailed information of each stable isotope's corresponding mineralogy recorded during sampling was used to make the correction (the figure with transformed and untransformed values will be added in the supplementary section).

Third, replication among samples of the same age is not particularly convincing, raising questions about the controls on isotopic values.

Response: We are not sure what the reviewer is specifically addressing here, but our best explanation is as follow:

Since Stalagmite ANJB-2 and MAJ-5 were collected from two different caves, i.e. 16 km apart, discrepancies between the two speleothems at the same age are expected, suggesting that local conditions could be one of the discrepancy factors. Another potential source for the discrepancy is the larger uncertainty of the younger ages due to low uranium and high detrital concentration. This U-Th aspect has been a challenge for several young stalagmites (e.g. Dorale et al., 2001; Lachniet et al., 2012) including samples from NW Madagascar (this study). While the utility of speleothems as a climate proxy largely depends on replication of stable isotope values, it is important to note that perfect stable isotope replication only occurs between stalagmites collected from the same cave chamber (e.g. Dong et al., 2011; Burns et al., 2016). Thus, to address this, we separated the stable isotope profiles and use dashed lines to connect similar profiles. [this paragraph has been inserted in the revised manuscript]

Fourth, several claims are poorly substantiated, incompletely referenced, or (to some degree or another) unsupported by the data.

Response: We carefully updated the citations and the references in our manuscript. We also carefully revised the interpretation accordingly.

We revised our interpretation of the data and included data from surrounding locations to put Madagascar into context. Some of the changes address RC2's comments (please see below).

Fifth, the writing is at times hard to follow.

Response: We did our best to carefully revise the manuscript. We incorporated requested changes in the specific comments by RC1 below. We also incorporated changes according to RC2's comment (e.g. narrowing discussion of the ITCZ and inserting discussion on other climate forcings, like IOD). Please see our responses to specific comments and please see our response to RC2.

1. Does the paper address relevant scientific questions within the scope of CP? Yes

2. Does the paper present novel concepts, ideas, tools, or data? No

Response: The data reported here are completely NEW and were only presented at scientific conferences. We have not submitted nor submitted this work to other journals but Climate of the Past, we completely disagree with a No answer to this question.

Although the ITCZ hypothesis, as a whole, is not a new concept, its application to the entire Holocene of Madagascar is NEW. The data reported in here thus fill the gaps in paleoclimate reconstruction in the Southwestern Indian Ocean region. Northwestern Madagascar's summer rainfall is monsoonal and it is linked to the southward migration of the ITCZ (e.g. Jury, 2003). Regional SST changes could influence its climate on an inter-annual basis [additional discussion incorporated in the manuscript per RC2], but one cannot ignore the influence of the ITCZ.

3. Are substantial conclusions reached? No

Response: In this study, we tested the climatic responses in Madagascar in accord to the latitudinal migration of the ITCZ, a very important climatic aspect that has been extensively used to understand tropical rainfall dynamics and global oceanic and atmospheric circulation on a longer-time scale (e.g. Fleitmann et al., 2007; Sinha et al., 2011; Schefuß et al., 2011; Sachs et al., 2009; Koutavas and Lynch-Stieglitz, 2004; Russell and Johnson, 2005; Brown and Johnson, 2005; Sinha et al., 2011; Leech et al., 2013). Our data suggest that when the ITCZ was located south when the Northern Hemisphere was cooler than the Southern Hemisphere, the climate in NW Madagascar was wetter. In contrast, when the ITCZ was located North when the Southern Hemisphere was relatively cooler than the Northern Hemisphere, the climate in NW Madagascar was drier. The deposition of stalagmite between 9.8 ka and 7.8 ka (MEHI) and after 1.6 ka BP (MLHI) suggest that climate during these intervals was wet, with sufficient moisture to supply the cave, and this could suggest a southward migration of the mean ITCZ position. The hiatus in deposition during the mid-Holocene, here labelled MMHI (between 7.8 ka to 1.6 ka), could generally reflect an interval of drier condition compared to modern conditions, suggesting that shallower chambers did not receive sufficient moisture to feed the stalagmites, thus they stopped growing. We revised some of the figures as well as the manuscript.

To substantiate our interpretation, we compared our data with other paleoclimate records from other locations (please see further below). We also added relevant discussion about changes in the surrounding ocean's sea surface temperature (such as IOD and ENSO, please see our response to RC2 below). We added a table and a map for regional comparison.

4. Are the scientific methods and assumptions valid and clearly outlined? No

Response: The manuscript has a stand-alone section that outline the methods, which was revised in response to reviewers' comments. This section is pasted below (please note that paragraph 1 is about radiometric dating, paragraph 2 is about petrography and mineralogy, and paragraph 3 is about stable isotopes). We do appreciate if RC1 is more specific about this.

"3.1. Methods

A total of 31 samples (22 for Stalagmite ANJB-2 and 9 for Stalagmite MAJ-5; Table S1 and S2) were analyzed to determine the age of the stalagmites' growth layer. Each sample is a representation of a long (~5 to 20 mm), narrow (~1-2mm), and shallow (~1 mm) trench, allowing us to extract 50 to 250 mg of $CaCO_3$ powder. We followed the chemical procedures described in Edwards et al. (1987) and Shen et al. (2002) when separating uranium and thorium. U/Th measurements of Stalagmites ANJB-2 and MAJ-5 were performed on a multi-collector ICP-MS of the University of Minnesota, USA and of the Stable Isotopes Laboratory of Xi'an, in Jiaotong, China. Instrumental details are provided in Cheng et al. (2013). Corrected ^{230}Th ages assume the initial ^{230}Th/^{232}Th atomic ratio of $4.4 \pm 2.2 \times 10^{-6}$. This is a ratio for a "bulk earth" or crustal material at secular equilibrium, with a ^{232}Th/^{238}U value of 3.8. The error of this "bulk earth" value is assumed to be ±50%. The error in the final "corrected age" incorporates this uncertainty. The radiometric data are reported as year B.P., where B.P. means Before Present and "present" represents the year 1950. Stalagmite chronologies were constructed using the StalAge1.0 algorithm of Scholz and Hoffman (2011) and Scholz et al. (2012), an algorithm using the Monte-Carlo simulation that is designed to construct speleothem age models. The algorithm can identify major and minor outliers and age inversions. The StalAge scripts were run on the statistics program R version 3.2.2 (2015-08-14). The age models were adjusted considering hiatal surfaces identified in the samples, using the approach of Railsback et al. (2013; see their Fig. 9).

Petrography and mineralogy of the two stalagmites were investigated by 1) examining polished surfaces and scanned images of the sectioned stalagmites, with which we determined variations in layer-specific width (e.g. Sletten et al., 2013; Railsback et al., 2014; Voarintsoa et al., 2017) and identified any diagenetic fabrics (e.g. Zhang et al., 2014) that could potentially alter the stable isotope values, 2) observing twelve oversized thin sections (3 x2 in) under the Leitz Laborlux 12 Pol microscope and the Leica DMLP equipped with QCapture of the Sedimentary Geochemistry Lab at UGA, and 3) analyzing about 30 mg of powdered spelean layers on a Bruker D8 X-ray Diffractometer in the Department of Geology of the University of Georgia. For $CaCO_3$ identification between calcite and aragonite, we used CoKα radiation at a 2θ angle between 20° and 60°.

For stable isotopes, subsamples ranging from 50 to 100 μg were manually drilled along the stalagmite's growth layers at the crest. The trench size is very small (<1.5 x 0.5 x 0.5 mm). Since a small mixture of calcite and aragonite could potentially change the δ^{18}O and δ^{13}C of the measured spelean layers (see for example Frisia et al., 2002), we carefully investigate the polished surface of the two stalagmites if features of diagenetic alteration are present (see for example fig. 2 of Zhang et al., 2014). During sampling, drilling and sample extraction was carefully done on individually discrete layer using the smallest drill-bit head (SSW-HP-1/4) to avoid potential mixing between calcite and aragonite. The mineralogy at the crest was noted during sampling for future correction. For the analytical methods, oxygen and carbon isotope ratios were measured using the Finnigan MAT-253 mass spectrometer fitted with the Kiel IV Carbonate Device of the Xi'an Stable Isotope Laboratory in China (ANJB-2; n=654) and using the Delta V Plus at 50°C fitted with the GasBench-IRMS machine of the Alabama Stable Isotope Laboratory in USA (MAJ-5; n=286). Analytical procedures using the MAT 253 are identical to those described in Dykoski et al. (2005), with isotopic measurement errors of less than 0.1 ‰ for both $\delta^{13}C$ and $\delta^{18}O$. Analytical methods and procedures using the GasBench-IRMS machine are identical to those described in Skrzypek and Paul (2006), Paul and Skrzypek (2007), and Lambert and Aharon (2011), with ±0.1 ‰ errors for both $\delta^{13}C$ and $\delta^{18}O$. In both techniques, the results were reported relative to Vienna PeeDee Belemnite (VPDB) and with standardization relative to NBS19. Inter-lab comparison of the isotopic results involved replicating every tenth sample of Stalagmite MAJ-5 on the MAT 253 mass spectrometer. The replicates suggest strong correlation (Fig. S4). Finally, transformation of the $\delta^{18}O$ and $\delta^{13}C$ of the primary aragonite was also done to compensate for the aragonite's inherent fractionation of heavier isotopes (e.g. Romanek et al., 1992; Kim et al., 2007; McMillan et al., 2005; Frisia et al., 2007) and to remove the mineralogical bias in isotopic interpretation between calcite and aragonite. Here, we refer to the laboratory tests on synthetic carbonates, which have shown a $\delta^{13}C$ enrichment of 1.7-1.8‰ (Rubinson and Clayton, 1969; Romanek et al. 1992) and a $\delta^{18}O$ enrichment of 0.8‰ in aragonite (Kim et al. 2007; Kim and O'Neil, 1997; Tarutani et al., 1969; Zhang et al., 2014) relative to calcite, to correct for the stable isotopes. Because none of the two stalagmites records any diagenetic features, our correction consists of subtracting 0.8‰ for $\delta^{18}O$ (Kim et al., 2007) and 1.7 ‰ for $\delta^{13}C$ (Romanek et al., 1992) for the aragonite. To give readers the freedom of interpreting and evaluating the stable isotope data with minimal influence from such correction, stable isotope time series in all the figures shown in the main manuscript only present the raw data. A figure showing both the untransformed and transformed values is added in the supplementary document."

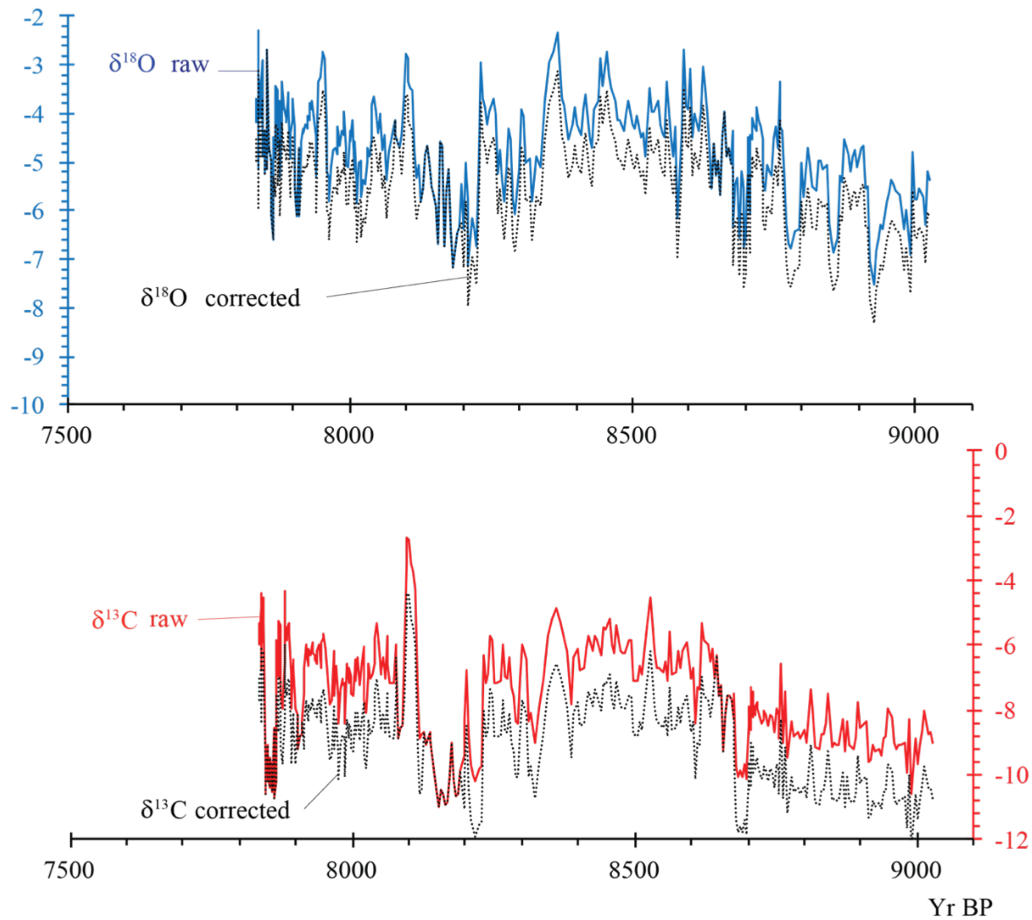

Figure_: Example of the stable isotope of oxygen and carbon profiles showing the raw and corrected values for ANJB-2 during the MEHI.

5. Are the results sufficient to support the interpretations and conclusions? No

Response: This paper reports on two stalagmites collected from two different caves, 16 km apart that reveal intervals of deposition during the MEHI and the MLHI, and interval of non-deposition during the MMHI. We might be wrong in our interpretation but we are certain we have sufficient information to let us better understand these stalagmites and to provide wise implications for paleoclimate study.

U-Th series

n= 22 (ANJB-2)

n= 9 (MAJ-5)

Stable isotopes

n= 654 (ANJB-2)

n=286 (MAJ-5) + 28 replicates (inter-lab comparison)

Mineralogy

Thin section (12)

X-ray diffraction (15 analysis)

Hand-sample observation

Scanning Electron Microprobe (figures will be added in the supplementary section of the revised manuscript)

Petrography

Type E

Type L

Layer-specific width, LSW (48 measurements)

In addition to our own records, we now included comments from RC2 and put our data into regional context and added a summary table and a map (please see pages 26-30 of this revision note).

6. Is the description of experiments and calculations sufficiently complete and precise to allow their reproduction by fellow scientists (traceability of results)?

7. Do the authors give proper credit to related work and clearly indicate their own new/original contribution? Not always 8. Does the title clearly reflect the contents of the paper? No

Response: We have incorporated more references to support the claims and interpretation. We might update the title slightly upon final revision of the manuscript.

9. Does the abstract provide a concise and complete summary?

10. Is the overall presentation well structured and clear? No

Response: We revised this manuscript, according to reviewers' comments and suggestion, and we hope that it is now much clearer (also please see response to specific comment for line 205 below)

11. Is the language fluent and precise? No

Response: We tried our best, and incorporated the requested changes in the specific comments.

12. Are mathematical formulae, symbols, abbreviations, and units correctly defined and used?

13. Should any parts of the paper (text, formulae, figures, tables) be clarified, reduced, combined, or eliminated?

14. Are the number and quality of references appropriate?

15. Is the amount and quality of supplementary material appropriate?

Specific comments follow:

For comments pertaining to lines 17 to 40, we completely revised the abstract, and considered many of the points that the reviewer made.

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18 – is this one cave or two?

corrected

23 – why no dates associated with the middle Holocene?

we added the date (sorry it was an editing mistake)

27 – when?

27 - "globally colder" is a little confusing; the interhemispheric temperature gradient is responsible for determining mean global ITCZ position.

30 – when?

33 – is "exemplified" the correct word here?

37 – here is the missing mention of hemispheric temp gradient. I suggest making this explicit earlier in the abstract.

39-40 – delete this sentence

Here we copy the revised abstract below:

"Petrographic features, mineralogy, and stable isotopes from stalagmites ANJB-2 and MAJ-5 from Anjohibe and Anjokipoty caves allow distinction of three intervals of the Holocene in northwestern Madagascar. The Malagasy early Holocene interval (MEHI, between ca. 9.8 and 7.8 ka) and the Malagasy late Holocene interval (MLHI, after ca. 1.6 ka) record evidence of stalagmite deposition. The Malagasy middle Holocene Interval (MMHI, between ca. 7.8 ka and 1.6 ka), however, is marked by a depositional hiatus lasting for ca. 6500 years.

The simplest interpretation of the MEHI, MMHI, and MLHI in NW Madagascar involves changes in the cave's hydrologic system and changes in vegetation that were in turn linked to climate. Stalagmite deposition during the MEHI and the MLHI suggests that these intervals were relatively wetter; whereas the long-term depositional hiatus at a Type L surface suggests that the MMHI was relatively drier. The alternating "wet/dry/wet" during each of these Holocene intervals could be linked to the long-term migration of the Inter-Tropical Convergence Zone (ITCZ). When the ITCZ's mean position was further south, NW Madagascar experienced wetter conditions, such as during the MEHI and MLHI, and when it moved north, NW Madagascar climate became drier, such as during the MMHI. A similar wet/dry/wet succession during the Holocene has been reported in neighboring locations, such as southeastern Africa.

Stable isotope records also suggest that although the MEHI and MLHI were wetter, the correlation between $\delta^{18}O$ and $\delta^{13}C$ in the MEHI suggest that the early Holocene vegetation closely responded to changes in climate. In contrast, the weaker correlation between $\delta^{18}O$ and $\delta^{13}C$ and the positive shift in $\delta^{13}C$ in the MLHI suggest that the late Holocene vegetation was controlled by something other than climate, and the plausible explanation for such changes is the practice of swidden agriculture, as reported in previous literature.

Beyond these three subdivisions, the evidence of the 8.2 ka event in the stalagmite records also suggests that climate in Madagascar was sensitive to abrupt climate changes, such as the abrupt influx of the Laurentide Ice Sheet meltwater to the North Atlantic. The freshwater influx into the North Atlantic, known to have weakened the Atlantic Meridional Overturning Circulation (AMOC), may also have led to an enhanced temperature gradient between the two hemispheres, i.e. cold NH and warm SH, shifting the mean position of the ITCZ further south. This would have brought wet conditions in the SH monsoon regions, such as northwestern Madagascar, and dry conditions in the NH monsoon regions, including the regions of Asian Monsoon and the East Asian Summer Monsoon.

This is all relevant because Madagascar's position in the southwestern Indian Ocean makes it an ideal candidate to test for the latitudinal migration of the ITCZ beyond the seasonal scale. Madagascar is also susceptible to several climatic forcing mechanisms, such as the Indian Ocean Dipole (IOD), the El-Niño Southern Oscillation (ENSO), and other sea surface temperature (SST) anomalies in the surrounding oceans. Understanding such relationship is fundamental in understanding regional climate and global oceanic and atmospheric circulation, which could potentially be useful in future climate prediction."

43 – delete "the"

deleted

49 – delete "the"

deleted

51 – reword as "a particularly"

done

52 – ITCZ was previously defined

Response: In the previous version of the manuscript, the ITCZ was defined in the abstract. In the revised manuscript, we defined the first acronym at the beginning in the introduction, and used the ITCZ acronym for the remainder of the text.

61 – reword "variability of growth-specific width" as "growth laminae"

Response: It is the layer-specific width as previously defined in the literature (e.g. Sletten et al., 2013; Railsback et al., 2014) as commented above (page 4).

61 - do not capitalize "cave"

corrected

90 – wasn't replication already discussed on line 42 (Line 85-89)

Response: We revised that section 2.1 (now it is section 2.2 because we added a basic section about stalagmite before it), and deleted the repeated sentence.

Copied below is the new 2.2. Regional environment updated content:

"Two stalagmites, ANJB-2 and MAJ-5, were collected from Anjohibe and Anjokipoty Cave, respectively, in the Majunga region of northwestern Madagascar (Fig. 1). The two caves have provided many insights about the paleoenvironmental and archaeological history of northwestern Madagascar (e.g. Burney et al., 1997, 2004; Brook et al., 1999; Gommery et al., 2011; Jungers et al., 2008; Vasey et al., 2013; Burns et al., 2016).

Anjohibe (S15° 32' 33.3"; E046° 53' 07.4") and Anjokipoty (S15° 34' 42.2"; E046° 44' 03.7") are about 16.5 km apart (Fig. 1c). Their location in the zone visited by the ITCZ (e.g. Nassor and Jury, 1998; Jury, 2003) makes them ideal sites to test for the latitudinal migration of the ITCZ (e.g. Chiang and Bitz, 2005; Broccoli et a., 2006; Chiang and Friedman, 2012; Schneider et al., 2014). The ITCZ brings north or northwesterly monsoon winds to Madagascar during austral summers, in a pattern that the Service Météorologique of Madagascar calls the "Malagasy monsoon". Majunga has a tropical savanna climate (Aw) according to the Köppen-Geiger climate classification, with a distinct wet summer (from October to April) and dry winter (May-September). The mean annual rainfall is around 1160 mm. The mean maximum temperature in November, the hottest month in the summer, is about 32°C. The mean minimum temperature in July, the coldest month of the dry winter, is about 18°C (Fig. 1b)."

Please note that in response to RC2 suggestions, we added an independent section revising the climate of Madagascar and the modern anomalies observed in the surrounding locations.

100 – "long-term" is vague; records of what?

Response: We revised the sentence as follow:

Long-term *paleoclimate* records from the same region are even scarcer, and to our current knowledge, the only scholarly published peer-reviewed articles that report on paleoclimate records covering period longer than 3 ka are sediment cores collected from Lake Mitsinjo (3,500 yr. BP; Matsumoto and Burney, 1994) and cave sediments from Anjohibe Cave (40,000 yr. BP; Burney et al. 1997).

101 – "longer" vague (see previous comment)

see our response to line 100 (previous response)

112 – "chronologies were" (now at line 143)

Corrected

133 – I am not sure that the correction for carbon isotopic fractionation between calcite and aragonite in speleothems has been adequately explored. As a result, I am uncertain if this part of the results will hold up.

Author's note: [also please refer to earlier response at pages 6-12]

- I am sorry for the confusion here, the expression "$\delta^{18}O$ and $\delta^{13}C$" in the sentence "Finally, the $\delta^{18}O$ and $\delta^{13}C$ of the spelean aragonite were transformed, by a subtraction of 1.7 ‰ (Romanek et al., 1992) and 0.8‰ (Kim et al., 2007) respectively" should be "$\delta^{13}C$ and $\delta^{18}O$". [It is now corrected and more references have been added].
- We provided relevant answers in the response to general comments above. A detailed response to this comment is also provided earlier (see pages 6-12), and we considered this comment in the revised manuscript.
- The isotopic fractionation used here has also been used repeatedly by our group in peer-reviewed publications (Sletten et al., 2013; Liang et al., 2015; Railsback et al., 2016; Voarintsoa et al., 2017) and other groups (e.g. Holmgren et al., 2003) with no objections from reviewers and no subsequent comments from readers.
- Recently, a group of researchers used a slightly greater isotopic correction of +2.5‰ for $\delta^{13}C$ for aragonite (Scroxton et al., 2017, p. 29), which is referenced from literatures reporting only for $\delta^{18}O$ correction (Kim et al., 2007; Kim and O'Neil, 1997; Tarutani et al., 1969). Kim et al. (2007), Kim and O'Neil (1997), and Tarutani et al. (1969) never reported a value of +2.5‰ for $\delta^{13}C$ in their oxygen experiment, thus we kept the $\delta^{13}C$ value of 1.7 ‰ in the correction.

Detailed response to "*I am not sure that the correction for carbon isotopic fractionation between calcite and aragonite in speleothems has been adequately explored***":** We explored different literatures (old and modern) reporting on calcite and aragonite's isotopic fractionation (the following text will be added in the supplementary section):

Fractionation factors of carbon and oxygen stable isotopes between the solution and the precipitated mineral are significantly different between aragonite and calcite (Kim and O'Neil, 1997; Tarutani et al., 1969; Grosman and Ku, 1986; Kim et al., 2007; Rubinson and Clayton, 1969; Turner, 1982; Romanek et al., 1992). For example, several studies have shown stable isotope enrichment in aragonite relative to calcite at similar conditions. A $\delta^{13}C$ enrichment of around 2.5‰ in the original aragonite layer from Stalagmites CL26 and CL27 (McDermott et al., 1999) was reported to approximate the theoretical expected difference between aragonite and calcite (e.g Morse and MacKenzie, 1990). Laboratory experiments on calcium carbonate at 25°C have shown that $\delta^{13}C$ values of synthetic aragonite precipitated from a bicarbonate solution is enriched by ~1.4‰ and ~1.8‰ relative to calcite (Rubinson and Clayton, 1969; Turner, 1982; Romanek et al., 1992), while $\delta^{18}O$ values is enriched by ~0.6‰ and ~0.8‰ (Tarutani et al., 1969; Kim and O'Neil, 1997; Grosman and Ku, 1986; Kim et al., 2007). Later experiments and investigations agree with these previous data (e.g. McMillan et al., 2005; Zhang et al., 2014). Some other authors have reported larger difference (16‰) between calcite $\delta^{13}C$ and aragonite $\delta^{13}C$ in speleothems (e.g. Frisia et al., 2002). We assume, based on the data presented in Frisia et al.'s (2002) specific study, that this large difference is not solely caused by aragonite's inherent fractionation of heavier isotopes at time of deposition, but also it could be associated with natural causes, such as the difference in cave environment, the degree of kinetic fractionation, and the sourcing of $\delta^{13}C$ (e.g. vegetation and biomass activity above the cave). Consequently, it would be wise to use the laboratory results from the experimental studies, i.e. the $\delta^{13}C$ value of 1.8‰ (Rubinson and Clayton, 1969; Romanek et al., 1992) to correct for the differential fractionation between calcite and aragonite because the different natural variables and parameters, in such experiments, that could alter $\delta^{13}C$ values are well under control (i.e. free of other natural factors' influences).

142 – looking at the data table in Supp Materials, it appears that ANJB-2 (sometimes labeled as ANJ-B-2) has a wide range in U abundance. So why the s.d. of 0? 144 – Providing this level of U and Th abundance data is not particularly useful. I would simply refer the reader to the relevant data table. What is missing that should be included here is a discussion of 238/232 ratios in each sample, what 232/232 value was used to correct for inherited 230 (and how this value was derived), and how well the ages fall in correct stratigraphic order. Most ages look quite good but some late Holocene dates have larger errors. These deserve some discussion.

Response: We apologize for the inconsistencies in the labeling, we revised it and labeling for ANJB-2 is now consistent throughout the table.

Authors' note: 238/232 ratio is not precise. Likewise, 232/232 would presumably equal 1 and we have never seen that 232/232 ratio being used in U-Th results report.

Detailed responses:

For the methodology, we added the following section:

"A total of 31 samples (22 for Stalagmite ANJB-2 and 9 for Stalagmite MAJ-5; Table S1 and S2) were analyzed to determine the age of the stalagmites' growth layer. Each sample is a representation of a long (~5 to 20 mm), narrow (~1-2mm), and shallow (~1 mm) trench, allowing us to extract 50 to 250 mg of $CaCO_3$ powder. We followed the chemical procedures described in Edwards et al. (1987) and Shen et al. (2002) when separating uranium and thorium. U/Th measurements of Stalagmites ANJB-2 and MAJ-5 were performed on the multi-collector ICP-MS of the University of Minnesota, USA and of the Stable Isotopes Laboratory of Xi'an, in Jiaotong, China. Instrumental details are provided in Cheng et al. (2013). Corrected ^{230}Th ages assume the initial $^{230}Th/^{232}Th$ atomic ratio of $4.4 \pm 2.2 \times 10^{-6}$. This is a ratio for a "bulk earth" or crustal material at secular equilibrium, with a $^{232}Th/^{238}U$ value of 3.8. The error of this "bulk earth" value is assumed to be ±50%. The error in the final "corrected age" incorporates this uncertainty. The radiometric data are reported as year B.P., where B.P. means Before Present and "present" represents the year 1950 (for details, see footnote of Table S1 and Table S2). Stalagmite chronologies were constructed using the StalAge1.0 algorithm of Scholz and Hoffman (2011) and Scholz et al. (2012), an algorithm using the Monte-Carlo simulation that is designed to construct speleothem age models. The algorithm can identify major and minor outliers and age inversions. The StalAge scripts were run on the statistics program R version 3.2.2 (2015-08-14). The age models were adjusted considering hiatal surfaces identified in the samples, using the approach of Railsback et al. (2013; see their Fig. 9)."

For the discussion, we added the following section:

"Results from radiometric analyses of the two stalagmites are presented in Table S1 and Table S2. Corrected ^{230}Th ages suggests that Stalagmite ANJB-2 was deposited between ca. 8977±50 and 161±64 yr. BP, and Stalagmite MAJ-5 was deposited between ca. 9796±64 and 150±24 yr. BP. These ages collectively indicate stalagmite deposition at the beginning (between 9.8 and 7.8 ka BP) and at the end of the Holocene (after ca. 1.6 ka BP). In both samples, the older ages have small 2σ errors and they generally fall in correct stratigraphic order, except sample ANJB-2-120 and its replicate ANJB-2-120R, which were rejected because of the sample's high porosity and high detritals content. In contrast, many of the younger ages have larger uncertainties. This is mainly because many of the younger samples have very low uranium concentration and the detrital thorium concentration is also high, similar to what Dorale et al. (2001) reported. We also understand that the value for initial ^{230}Th correction, i.e. the initial ^{230}Th/^{232}Th atomic ratio of $4.4 \pm 2.2 \times 10^{-6}$ for a bulk earth with a ^{232}Th/^{238}U value of 3.8, in these samples could have slightly altered the ^{230}Th age of these younger samples, leading to larger uncertainties (such as discussed by Lachniet et al., 2012). We encountered similar problems while working on other younger samples from the same cave, however, comparison of stable isotope profiles of stalagmites that were corrected using the bulk earth values with stable isotope profiles of other stalagmites that were corrected using the isochron method suggest that the best fit age model from each method has produced similar results (see Fig. S7; also see Voarintsoa et al., 2017)."

148 – The wording here is confusing. Why argue for some continuous growth intervals but define others as separated by hiatuses?

Response: We rephrased the section to make it clearer. We copied the changes below:

"The StalAge model and petrographic investigation of the two stalagmites suggest three distinct intervals of the Holocene (Fig. 2): (1) evidence of $CaCO_3$ deposition between ca. 9.8 and 7.8 ka BP, (2) a noticeable long-term depositional hiatus between ca. 7.8 and 1.6 ka BP, and (3) resumption of $CaCO_3$ deposition after ca. 1.6 ka BP. In the rest of the paper, these intervals are referred to as the Malagasy early Holocene interval (MEHI), Malagasy mid-Holocene interval (MMHI), and Malagasy late Holocene interval (MLHI) respectively."

154 – these are enormous ranges in d18O and d13C. 161 – drop the hundreths place in the stable isotope values (where they are included). It complicates the paper but doesn't have any relevance for interpretation.

Response: We revised this section, and all the values are now with only one significant figure.

205 – this basic introduction should be presented much earlier in the paper if readers who require it are going to glean any meaningful information from the stable isotope results.

Response: The reviewer's concern about putting this basic introduction at the beginning of the manuscript is fully understandable. We moved the first paragraph (lines 205-212, from the submitted manuscript) to become a new subsection entitled "2.1. Introduction to stalagmites" in Section 2. We however kept the information pertaining to the "Paleoclimate significance of stalagmite and non-growth: implications for paleohydrology" at the beginning of the discussion section to remind the readers that the timing of deposition and non-deposition of these stalagmites could be the primary key to understand the overall paleohydrology during the Holocene in the studied region.

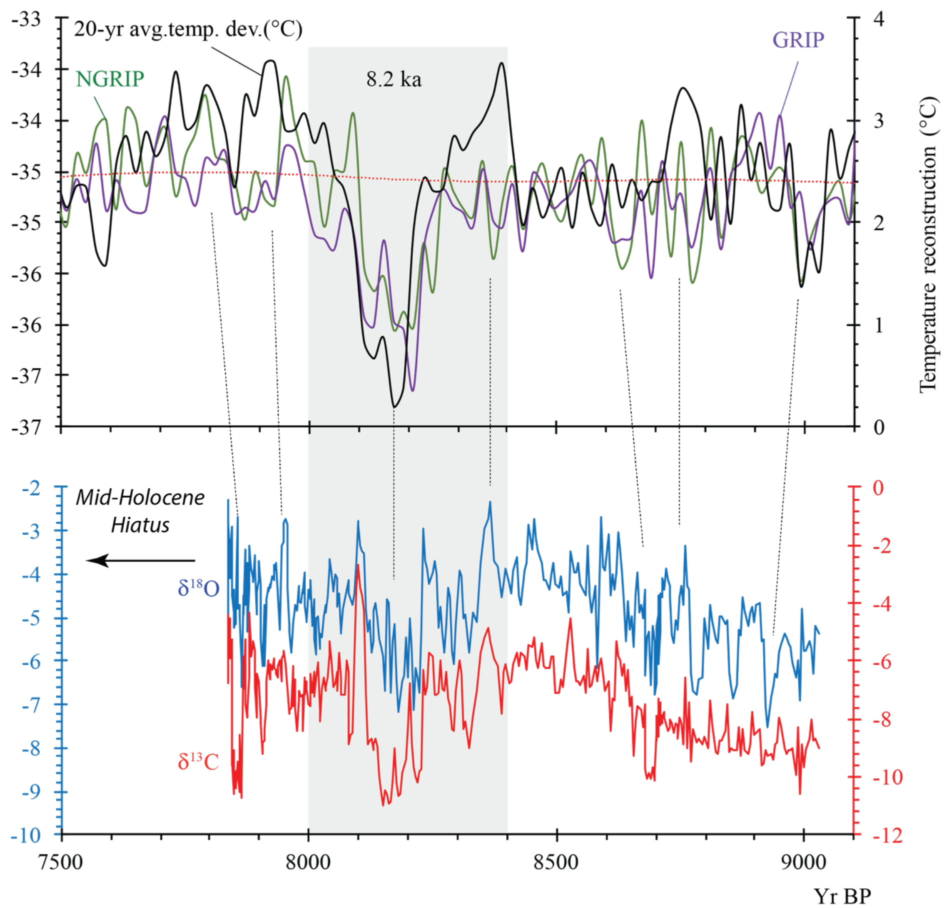
272 – relative to what time interval?

Response: We added "relative to modern climate" (and this is the reason we had Fig. S9: a model figure to understand the climate in NW during each of the three intervals of the Holocene) [In fact, this figure can be moved from the supplementary to the revised manuscript to illustrate the wet/dry/wet interpretation].

276 – I guess, but the record spans so little time that it's hard to get a clear sense of how anomalous this 8.2 isotopic excursion actually is.

Response: Instead of arguing that this is anomalous, and to avoid over-interpretation of the data, we rephrased the sentence as follow: "One striking aspect of the Stalagmite ANJB-2 $\delta^{18}O$ and $\delta^{13}C$ records is that they parallel the $\delta^{18}O$ of the Greenland ice core records at ca. 8.2 ka BP".

In addition, we updated the figure (copied below) to show the relationship in a clearer way (we zoomed it to show the interval between 7.8 and 9.1 ka BP).



278 – "suggest"? The mineralogical composition should be defined precisely (even down to percent calcite or aragonite). Or do you mean to suggest that it may have originally been aragonite but was altered to calcite?

Response: No, the calcite is not a diagenetic product of aragonite as suggested by the following evidence. First, the polished surfaces of the two stalagmites don't show evidence of fiber relicts and textural ghosts such as observed in Juxtlahuaca Cave in southwestern Mexico (Lachniet et al. 2012) and in Shennong Cave in southeastern China (Zhang et al., 2014). Second, the laminations in the thick layer of calcite were not altered (see figure below). Third, petrographic comparison with known examples of primary and secondary calcite observation under microscope (e.g. Railsback et al., 1997, 2002; Railsback, 2000; Perrin et al., 2014) suggest that the calcite in our stalagmites lacks the characteristics noted in secondary spelean minerals. Overall investigation of the stalagmites suggests that both minerals of aragonite and calcite in Stalagmite ANJB-2 and Stalagmite MAJ-5 are primary minerals. [This explanation has been added to the revised manuscript.]

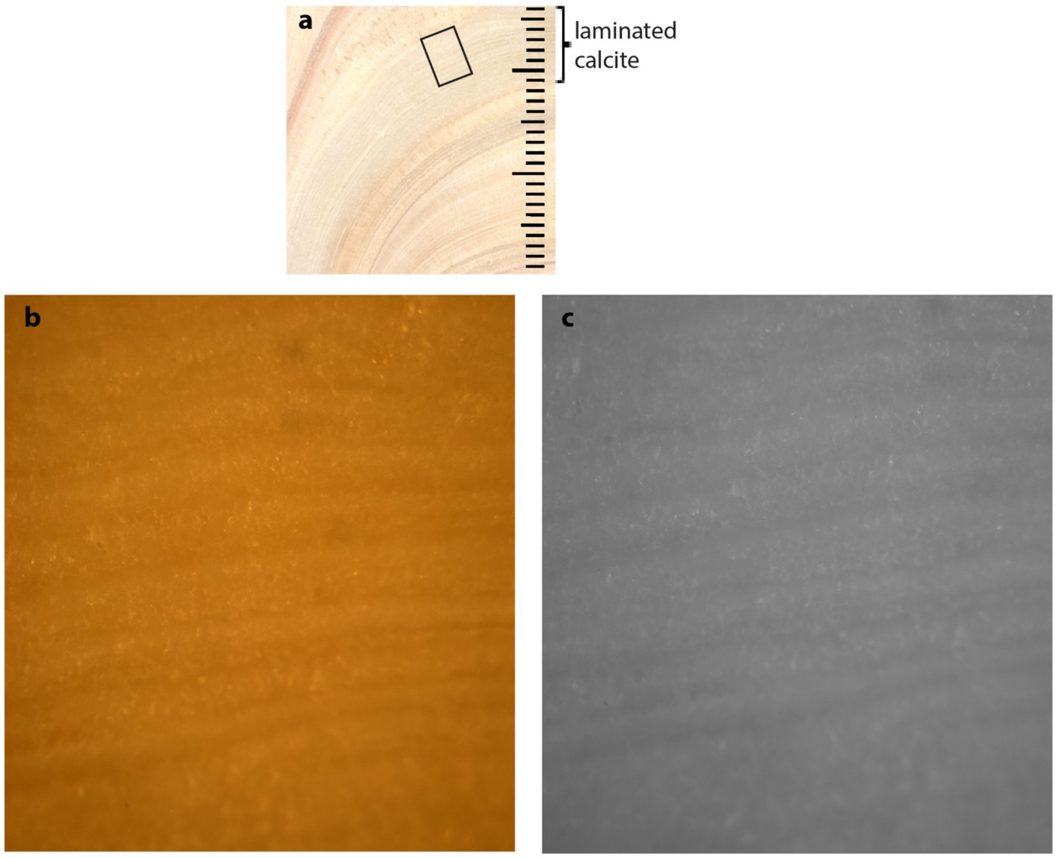


Figure__: Photograph showing the preserved lamination in the layer of calcite at 8.2 ka layer. (a) Scanned image of a section of Stalagmite ANJB-2 where the 8.2 was identified. (b) Photograph using true color under plain light. (c) Photograph using black and white filter.

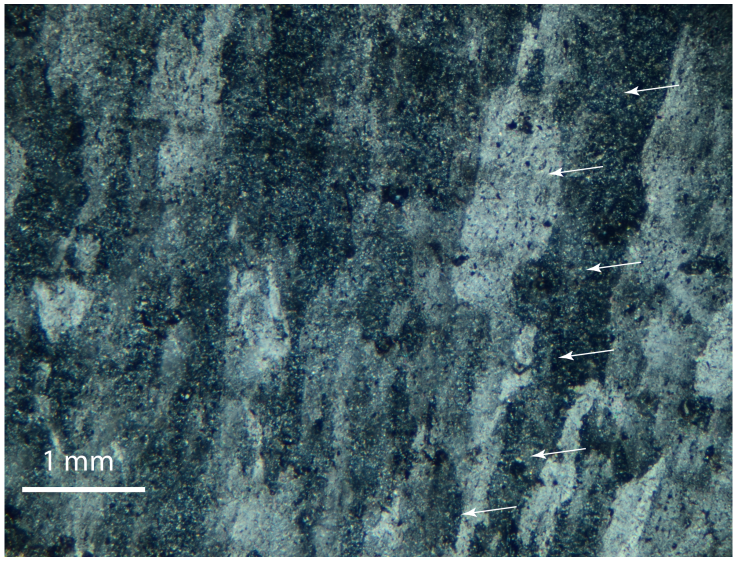


Figure__: Microphotograph of a columnar calcite with the alternating lamination revealed at the 8.2 ka event. Darker laminations, as seen in earlier photograph, are indicated with an arrow.

291 – missing a chance to fit this finding into a large context. What other regional records (African, south Asian) record the 8.2 event and what is the nature of these records?

Response: We added the regional comparison with the 8.2 ka in the sub-section dedicated for the 8.2 (in the revised manuscript). Here we copied the section where we incorporated this regional comparison:

"Understanding the AMOC's influence on Madagascar's hydroclimate could help us better understand the global atmospheric and oceanic circulation in the SH. Increased freshwater flux to the North Atlantic decreases the formation of the North Atlantic Deep Water, reducing the meridional heat transport (Barber et al., 1999; Clarke et al., 2001; Daley et al., 2011; Vellinga and Wood 2002; Dong and Sutton 2002, 2007; Dahl et al. 2005; Zhang and Delworth 2005; Daley et al., 2011; Renssen et al., 2001). Weakening of the AMOC would ultimately cause a widespread cooling in the NH regions (e.g. Clarke et al., 2001; Thomas et al., 2007) but warming in the SH regions (Wiersma et al., 2011; Wiersma and Renssen, 2006). This "cold NH–warm SH" climate response is similar to the "bipolar seesaw" effect, well-known during the last glacial (e.g. Crowley, 1992; Broecker, 1998). The interhemispheric temperature difference between the NH and SH from such effect could be the driver of the southward displacement of the mean position of the ITCZ during the 8.2 ka abrupt cooling event. This in turn could have led to an intensified Malagasy monsoon in NW Madagascar during austral summers, a phenomenon identical to the South

American Summer Monsoon, identified in Brazil (e.g. Cheng et al., 2009). Wetter conditions were also reported in eastern and southeastern Africa (e.g. Schefuß et al., 2011; Konecky et al., 2011; Tierney et al., 2008). In contrast, regions in the NH monsoon regions became dry as the Asian Monsoon and the East Asian Monsoon became weaker (e.g. Wang et al., 2005; Dykoski et al., 2005; Cheng et al., 2009; Liu et al., 2013)."

295-297 – I don't understand this sentence. Is this saying what you mean it to say?

Response: Apologize for the confusion. We carefully revised this section and the content of this section 5.2.2 is quite new. (as we stated earlier, the discussion section has been carefully revised).

373 – there are a lot studies to cite here. I am not sure self-citing is most appropriate in this context.

Response: Sorry, this is my mistake. I had a string of citations that are now included to support the claim.

377 – my reading of much of the SH paleoclimate literature suggests a dominance of NH insolation.

Response: Good point, but NH insolation is not sufficient. We specifically emphasized in our interpretation that "high winter insolation in the SH could have been responsible for the southward migration of the ITCZ during the early Holocene" (possibly identical to case 2 in our model in Fig S9).

408 – is "he" appropriate useage for Climates of the Past?

This is corrected

416 – similar findings were made based on lakes and speleothems in South America, and thus it may be worth citing some of this work here.

Response: We added the following: "This northward shift in the mean position of the ITCZ at 6 ka is consistent with drier conditions, i.e. weaker South American Summer Monsoon (e.g. Cruz et al., 2005; Seltzer et al., 2000; Wang et al., 2007; but see also Fig. 9 of Zhang et al., 2013) but wetter conditions in the northern tropics (e.g. Adkins et al., 2006; Dykoski et al., 2005; Fleitmann et al., 2007; Gasse, 2000; Haug et al., 2001; Weldeab et al., 2007; Zhang et al., 2013).

475 – does the Gulf Stream actually shut down when AMOC slows? Need to cite a modeling stud to support this claim.

Response: Since we revised the discussion section in its entirety, we also revised the content of the subsection about the 8.2 ka event. Here is the revised version copied below:

"The 8.2 ka event, a significant short-lived cooling of the early Holocene (Alley et al., 1997), is an ideal timeframe to investigate the "ocean-land-atmosphere" relationships during the early Holocene. It is revealed in northwestern Madagascar records as a wet interval (Figs. 3 and 7). A more fundamental impact of the changes in the AMOC is the alteration of the temperature gradient between the two hemispheres, known to have been responsible for the latitudinal shift of the ITCZ in the tropical Atlantic (e.g. Dong and Sutton, 2007; Delworth et al., 2008, p. 309). The 8.2 ka event is a known interval of abrupt freshwater influx from the melting Laurentide Ice Sheet into the North Atlantic (Alley et al., 1997; Barber et al., 1999; Kleiven et al., 2008; Carlson et al., 2008; Renssen et al, 2010; Wiersma et al., 2011; Wanner et al., 2015). It is equivalent to the sharp peak of the Bond cycle number 5 (Bond et al. 1997, 2001). This influx of meltwater altered the density and salinity of the NADW. Thornalley et al. (2009) reported a decrease in the NADW salinity to approximately 34 p.s.u. during the early Holocene.

Understanding the AMOC's influence on Madagascar's hydroclimate could help us better understand the global atmospheric and oceanic circulation in the SH. Increased freshwater flux to the North Atlantic decreases the formation of the North Atlantic Deep Water, reducing the meridional heat transport (Barber et al., 1999; Clarke et al., 2001; Daley et al., 2011; Vellinga and Wood 2002; Dong and Sutton 2002, 2007; Dahl et al. 2005; Zhang and Delworth 2005; Daley et al., 2011; Renssen et al., 2001). Weakening of the AMOC would ultimately cause a widespread cooling in the NH regions (e.g. Clarke et al., 2001; Thomas et al., 2007) but warming in the SH regions (Wiersma et al., 2011; Wiersma and Renssen, 2006). This "cold NH–warm SH" climate response is similar to the "bipolar seesaw" effect, well-known during the last glacial (e.g. Crowley, 1992; Broecker, 1998). The interhemispheric temperature difference between the NH and SH from such effect could be the driver of the southward displacement of the mean position of the ITCZ during the 8.2 ka abrupt cooling event. This in turn could have led to an intensified Malagasy monsoon in NW Madagascar during austral summers, a phenomenon identical to the South American Summer Monsoon, identified in Brazil (e.g. Cheng et al., 2009). Wetter conditions were also reported in eastern and southeastern Africa (e.g. Schefuß et al., 2011; Konecky et al., 2011; Tierney et al., 2008). In contrast, regions in the NH monsoon regions became dry as the Asian Monsoon and the East Asian Monsoon became weaker (e.g. Wang et al., 2005; Dykoski et al., 2005; Cheng et al., 2009; Liu et al., 2013)."

729 – is the name for this reference correct? It is a hyphenated name in the text.

Response: Good eyes! The reference is now corrected.

Fig 5 and Fig 6 – It would be helpful to have the isotopes presented on the same scales oriented along the same horizontal lines so that the reader can assess how each stalagmite's isotopic trends and values compare with the other.

Fig 6 – I don't see the connection between solar and stalagmite isotopes here.

Response: For any comments pertaining to figures, we revised many of them (as listed in the summary, page 1) in the submitted manuscript to account for many suggestions and comments from RC1, SL, and RC2. Likewise, interpretation has been revised.

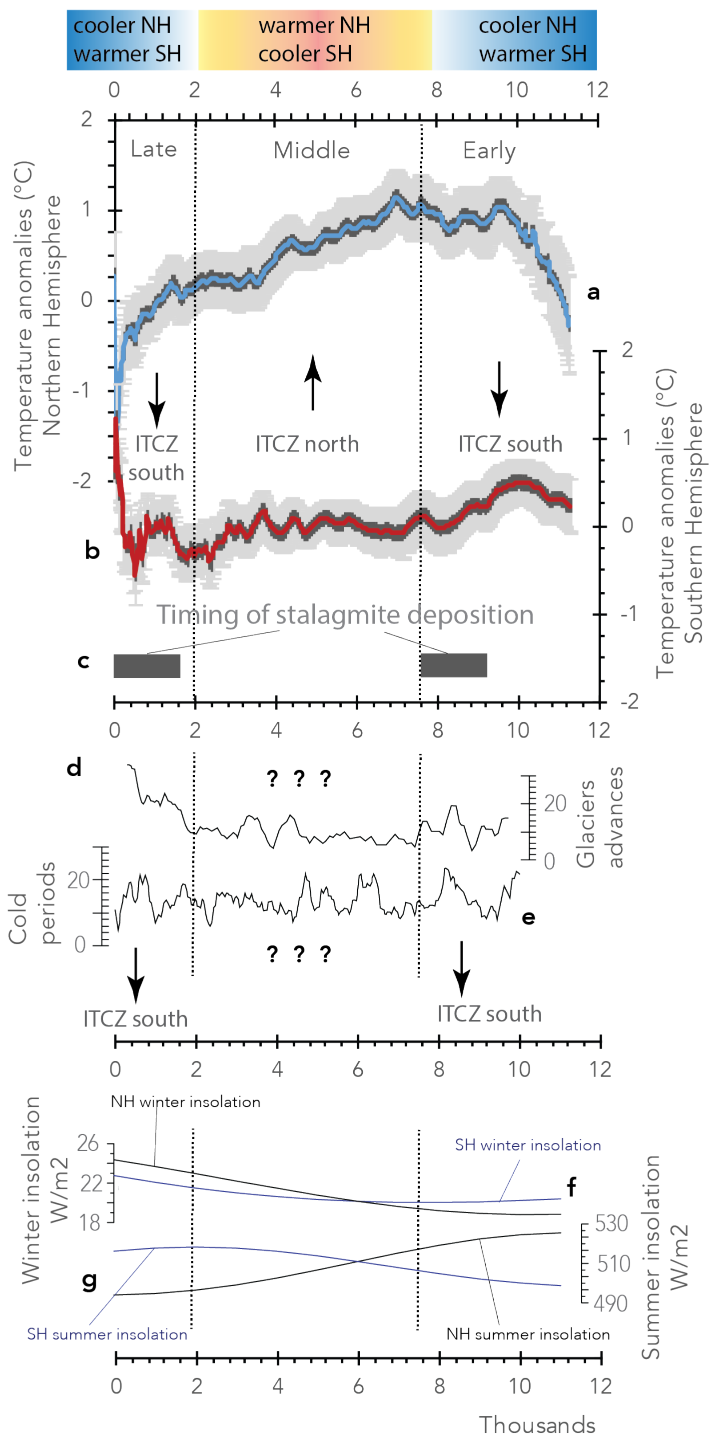


Figure__: Possible Holocene climate forcings responsible for the latitudinal migration of the ITCZ. Note the timing of stalagmite deposition coincides with cooler NH and warmer SH, agreeing with the concept that the ITCZ migrates toward warmer hemisphere. [details about this figure will be incorporated in the revised manuscript]

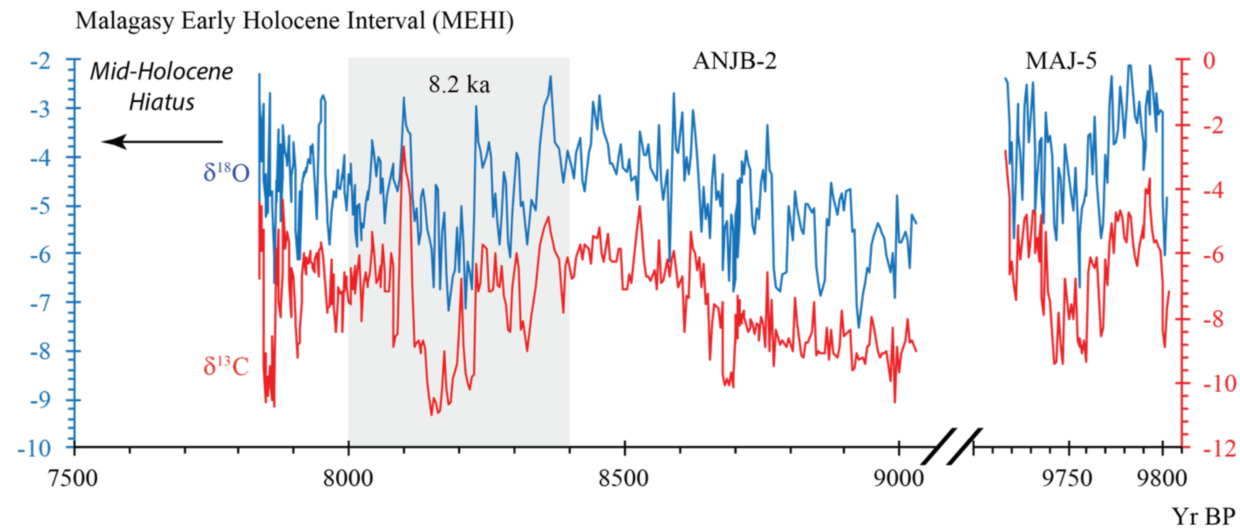


Figure__: Stable isotope profile during the Malagasy Early Holocene Interval (MEHI). The 8.2 ka event is characterized by a decreasing $\delta^{18}O$ and $\delta^{13}C$ values.

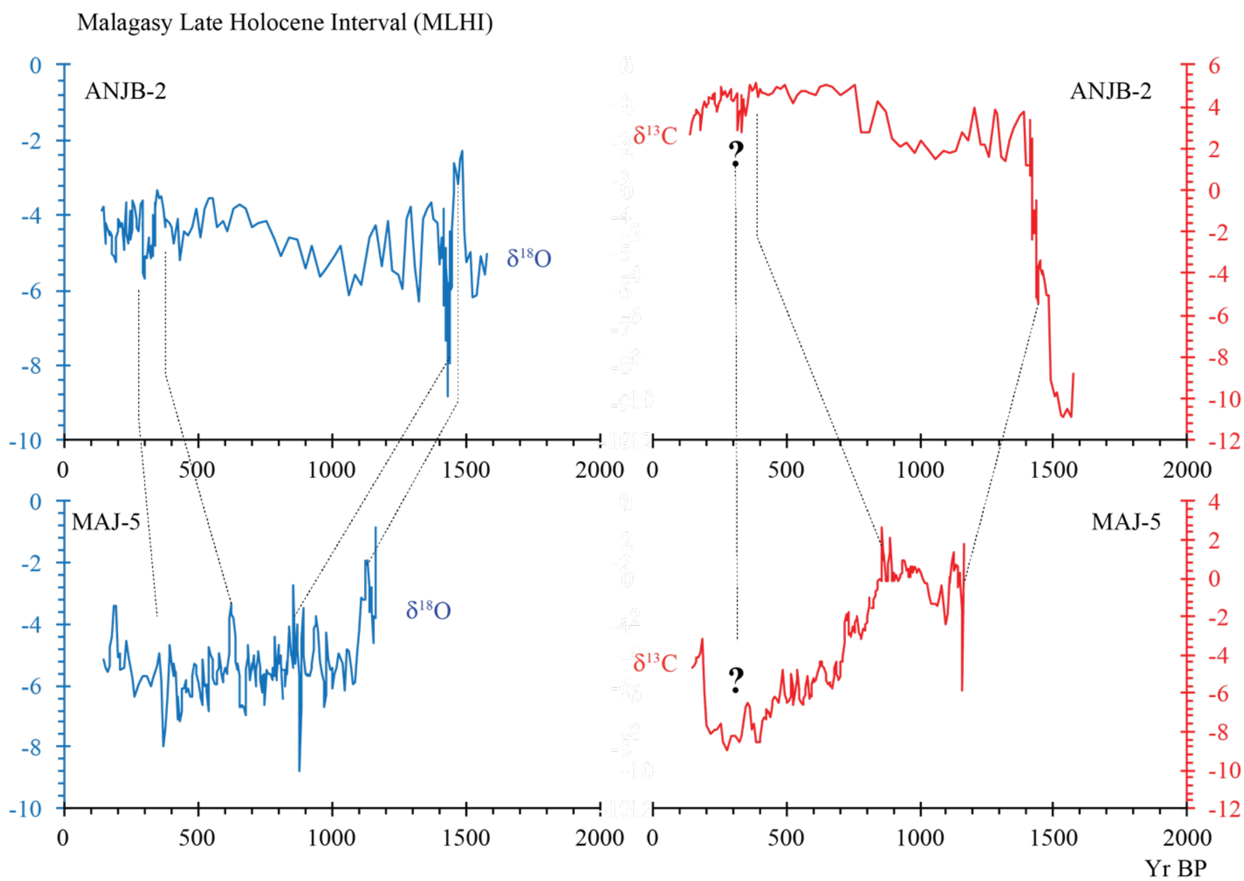


Figure__: Stable isotope profile during the Malagasy Late Holocene Interval (MLHI). Light dashed lines attempted to connect similar profile. Discrepancies exist between the stable isotope profiles because of the larger age uncertainties of the younger samples. The variability seen in $\delta^{13}C$ profile in both stalagmites could suggest highly disturbed landscape during the MLHI.

Short Comment *by* Sebastian Luening (**SL**)
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Received and published: 12 February 2017

This is an important new contribution on the palaeoclimate of Madagascar and the greater southeast African region. The link to the migrating / oscillating ITCZ and the influence of solar activity changes is very important and helps to better understand natural climate variability in the region.

Thank you!

The isotope curves contain additional information which is not fully covered in the discussion section of the paper. For example, I took a closer look at the time of the Medieval Climate Anomaly (1000-1200 AD) and noticed that the Anjohibe Cave records a general wet phase 850-1100 AD based on d18O.

Response: A discussion about this has been included, and it is copied below.

Wet conditions between ca. 850 and 1100 AD in Stalagmite ANJB-2 and Stalagmite MAJ-5, specifically coincide with glacial advances in the northern high latitudes (Holzhauser et al., 2005) and cooler interval of the Medieval Climate Anomaly, as suggested by a negative temperature anomaly in the NH (e.g. Büntgen et al., 2011; Mann et al., 1998; Mann and Bradley, 1999, see also Fig. ___, below), agreeing with the southward migration of the ITCZ and wet conditions in NW Madagascar.

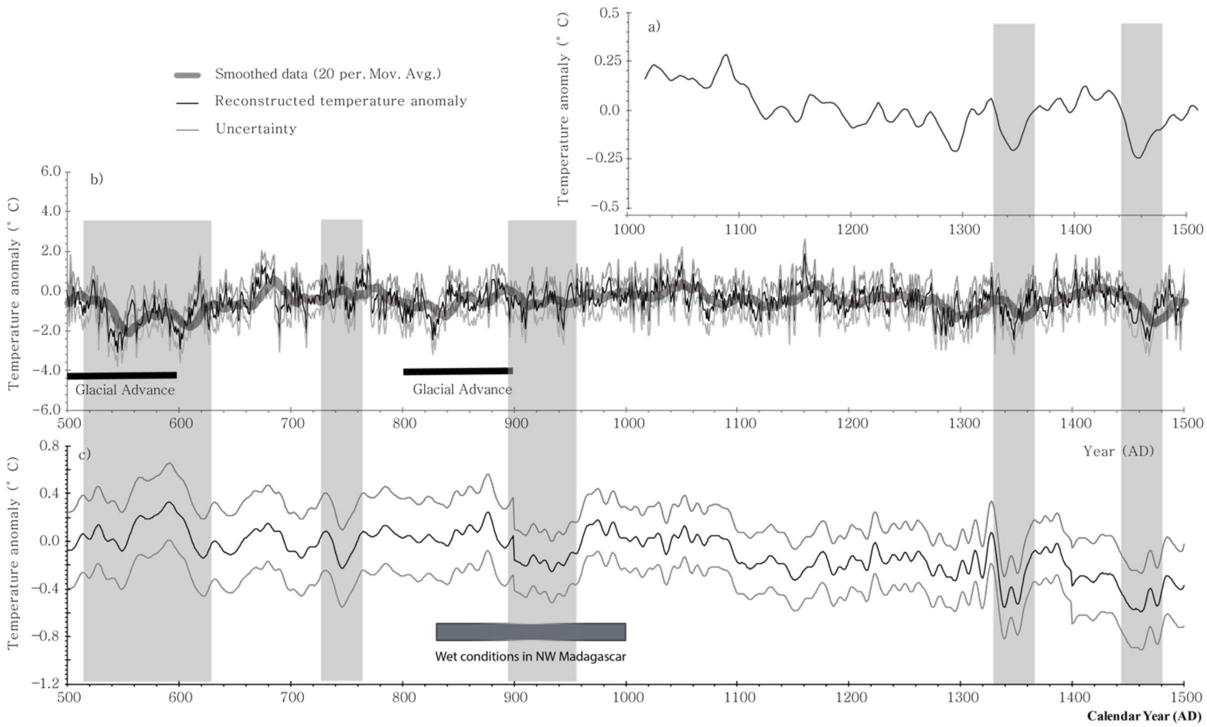

Fig__: Wet conditions in Madagascar (horizontal dark gray bar at bottom) matching with NH cooler conditions. [for details about this figure, please refer to Fig. S9 of Voarintsoa et al., 2017 Paleo 3—This figure will also be added in the supplementary document of the revised manuscript]

Notably, the d18O development in Anjokipoty Cave differs. Why? It is fully expected and it could be cave specific or just due to the larger uncertainties of the younger samples [please see our response to RC1 above on page 12]. A wetter MCA fits well with the bulk of other regional studies from the region (green dots in this regional MCA mapping project: http://t1p.de/mwp). Your map is impressive and it is a great compilation of all the available data. (as said earlier, discussion pertaining to that specific interval has been included)

It is unfortunate that the two d18O curves in Fig. 5b are plotted on top of each other, making it very hard to see the individual curves. I suggest you separate them for better readability.
As we mentioned in our response to RC1 above, we revised these figures to make it clearer (see page 34). The stable isotope profiles were separated as requested.

In the data supplement figure S7 you show datasets AB2 and AB3 without properly introducing them. Please add information on these datasets.

Yes, we added the pertaining information to make this figure clearer. Thank you.

Anonymous Referee #2 (RC2):

Received and published: 22 March 2017

This papers presents climate reconstruction obtained from two speleothems located in northwestern Madagascar. Three climatic episodes are identified based on change in ∂ 18O and ∂13C. The mid Holocene interval is represented by a hiatus that lasted from 7.8 to 1.6 ka. Petrology, mineralogy and stable isotopes are inferred to discuss changes in stalagmite physiognomy and geochemical composition and relate to climatic changes. The discussion on how to detect hiatuses in speleothems is very interesting with issues of broad interest. However several concerns that are listed below are preventing from allowing a publication of these results in their actual presentation.

1) a discussion on age results and age model is lacking.

Response: Considered (please also see our response to RC1 comment, p. 14-16 and 25-26 of this revision note)

2) results show several discrepancies between the two speleothems at a same age which are not commented. A presentation of the curves separately is needed with a discussion on the results.

Response: We commented on the discrepancies in the revision (copied below, also see earlier response on page 12). The curves are now shown separately.

"Since Stalagmite ANJB-2 and MAJ-5 were collected from two different caves, i.e. 16 km apart, discrepancies between the two speleothems at the same age are excepted, suggesting that local conditions could be one of the discrepancy factors. Another potential source for the discrepancy is the larger uncertainty of the younger ages due to low uranium and high detrital concentration. This U-Th aspect has been a challenge for several young stalagmites (e.g. Dorale et al., 2001; Lachniet et al., 2012) including samples from NW Madagascar (this study). While the utility of speleothems as a climate proxy largely depends on replication of stable isotope values, it is important to note that perfect stable isotope replication only occurs between stalagmites collected from the same cave chamber (e.g. Dong et al., 2011; Burns et al., 2016). Thus, to address this, we separated the stable isotope profiles and use dashed lines to connect similar profiles."

3) the results are never discussed at a regional scale and some important references are lacking from paleoclimate reconstructions in eastern Africa and Indian Ocean. The Holocene wet-dry-wet succession was already identified in several studies never cited here. The climate boundaries of the Holocene might be spatially limited but not nonexistent.

Response: It would be helpful from the reviewer to suggest some literatures that support his/her claim of "several studies", because my reading of many of the African paleoclimate reconstruction still suggests a lot of discrepancies. The challenges in paleoclimate regional comparison start from the length of the records and the nature of the records. More specifically, few high resolution, continuous, and well-constrained data of the Holocene interval are available to provide an even paleoclimate comparison. The discrepancies can also be purely explained by the methodologies and interpretation of the proxies used (e.g. Truc et al., 2013; Scott and Thackeray, 1987; Scott, 1999). They can be explained by the sensitivity of these proxies to changes in the environment and climate (e.g. Lee-Thorp et al., 2001; Holmgren et al., 2003; Sletten et al., 2013; Brook et al., 2010, 2015). It is also worth mentioning that climate in Africa is characterized by large degree of internal variability, typically observed at modern times (e.g. Lindesay, 1998; Nicholson, 1986, 1996; Nicholson et al., 2012; Hannaford and Nash, 2016), and this complexity could challenge the paleoclimate reconstruction.

Although this paper is not focused on reviewing the paleoclimate in these mentioned regions, the reviewer has made a good point at including some comparisons with other records from these surrounding locations. We indeed addressed this concern by adding a new section "regional comparison" along with a table and a figure to the discussion section:

"Despite the large discrepancies among paleoclimate reconstruction in southern Africa, comparison of the NW Madagascar records with other records from neighboring locations suggests that the Holocene wet/dry/wet succession reported in this study is not a local event. It is also identified in other locations. For example, hydrogen isotope compositions of the n-C_{31} alkane in GeoB9307-3 from a 6.51 m long marine sediment core retrieved about 100 km off the Zambezi delta suggest a similar wet/dry/wet climate during early, middle, and late Holocene respectively (Schefuß et al., 2011). Those changes correspond to changes in temperature around ~26.5°, 27.25°, 27°C, respectively, in the Mozambique Channel, as suggested by alkenone SST records from sediment cores MD79257 (Bard et al., 1997; Sonzogni et al., 1998). The Zambezi catchment is specifically relevant here because it is located at the southern boundary of the modern ITCZ, and thus it lies at similar climatic setting as NW Madagascar, and its sensitivity to the latitudinal migration of the ITCZ could parallel that of Madagascar. Likewise, temperature reconstruction from the Mozambique Channel could be used to link regional changes in paleorainfall with regional changes in temperature. A general overview of the Holocene climate in the African neighboring locations to Madagascar (Fig.__, see below) suggests a roughly consistent wetter and drier climate during the early and middle Holocene, respectively (Table 1, also see Gasse, 2000; Singarayer and Burrough, 2015). However, the late Holocene paleoclimate reconstruction is largely diverse. A single answer to this diversity is unlikely, but several overlapping factors, including the latitudinal migration of the ITCZ, changes in ocean oscillations and sea surface temperatures, volcanic aerosols, and anthropogenic influences could have played a major role in such variability (e.g. Nicholson, 1996; Gasse, 2000; Tierney et al., 2008; Truc et al., 2013). Those factors are outside the scope of this paper and will not be discussed here."

Table 1: Summary of the Holocene climate variability in SE Africa and SW Indian Ocean. The Holocene subdivision is relative to the MEHI, MMHI, and MLHI. "*w*" indicates "wet" (more rainfall) and "*d*" indicates "dry" (less rainfall). Please not that these inferences are relative and the temporal resolution of the sediment records are generally coarser than our stalagmite records. The most relevant paleoclimate records to NW Madagascar hitherto are indicated in stars (*)

					Holocene			
Location	**Time range**	**Lat.**	**Long.**	**Proxy**	**early**	**middle**	**late**	**References**
Lake Challa (a crater lake on the lower east slope of Mt Kilimanjaro)	0-25ka	3°19'S	37°42'E	BIT index from lake deposits	*w*	*d*	*w*	Verschuren et al., 2009
Lake Tanganyika NP04-KH04-3A-1K and NP04-KH04-4A-1K	0-60ka	6°42'S	29°50'E	TEX_{86} and $\delta D_{leaf\ wax}$ (‰ vs. SMOW)	*w*	*w/d*	*d*	Tierney et al., 2008
Lake Masoko	0-45ka	9°20.0'S	33°45.3'E	Low field magnetic susceptibility	*w/d*	*d*	*w*	Garcin et al., 2006
Lake Malawi	0-140ka	10°01.06'S 11°17.66'S	34°11.16'E 34°26.15'E	$C_{28}\delta D$ (‰ vs. SMOW)	*d/w*	*d*	*w*	Konecky et al., 2011

Lake Malawi M98-1P	0-25ka	10°15.9'S	34°19.1'E	BSi MAR	*w*	*w*	*d*	Johnson et al. 2002
Lake Malawi M98-2P	0-25ka	9°58.6'S	34°13.8'E	BSi MAR	*d*	*d/w*	*d/w*	Johnson et al. 2002
*Zambezi delta (GeoB9307-3)	0-17ka (130y resolution)	18°33.9'S	37°22.8'E	δD *n*-C_{31} alkane (‰ vs. SMOW)	*w*	*d*	*w*	Schefuß et al., 2011
*Indian Ocean (MD79257)	0-45ka	20°24'S	36°20'E	Alkenone SST record	*26.5°*	*27.25°*	*27°*	Bard et al., 1997; Sonzogni et al., 1998
Wonderkrater	0-20ka	24.4390°S	28.7507°E	Pollen	*w*	*w*	*d/w*	Truc et al., 2013 (note some discrepancies in interpretation with Scott and Thackeray, 1987; and Scott, 1999)
Tswaing Crater	0-200ka	25°24'29.26"S	28° 4'57.32"E	Sediment composition	*d*	*d/w*	*w*	(Partridge et al., 1997)
Lake Chilwa	0-44ka	15°30'S	35°30'E	OSL dating of sediment cores	*w*	*d*	*d*	Thomas et al., 2009

Cold Air Cave	0-25ka	24°1'S	29°11'E	Stalagmite T8	*w*	*d*	*d*	Lee-Thorp et al., 2001; Holmgren et al., 2003
*Lake Tritrivakely	0-40ka	19°47'S	46°55'E	Sediment magnetic properties and pollen	*d*	*d/w*	*w/d*	Gasse et al., 1994; Williamson et al., 1998; Gasse and Van Campo, 1998
*Anjohibe Cave	1-9ka	15.53°S	46.88°E	Stalagmite	*w*	*d*	*d?*	Wang and Brook., 2013; Wang, 2016

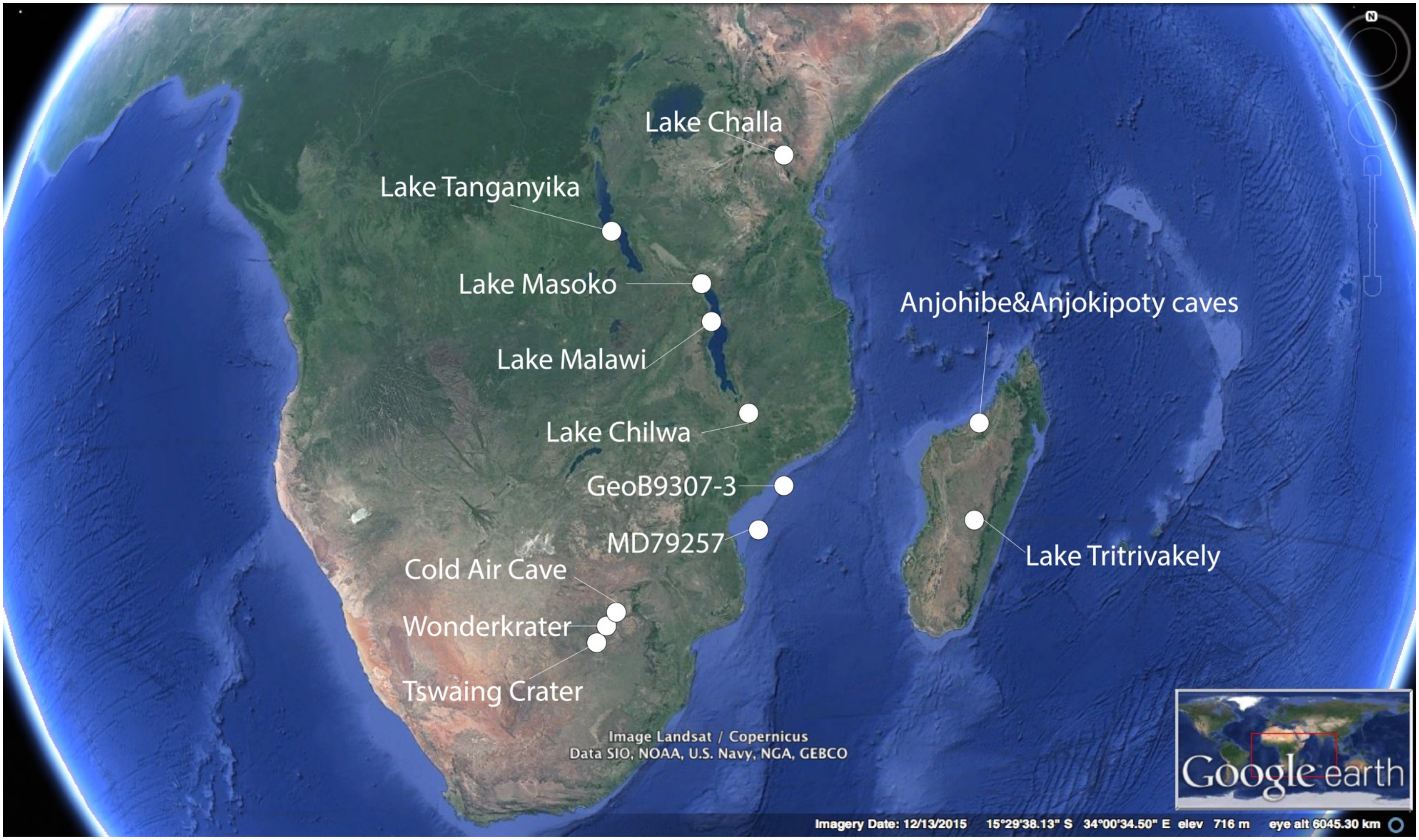

Figure__: Google earth image showing the location of the sites reported in Table 1. Most records reported from these sites are lake sediments, except for GeoB9307-3 (onshore off delta sediments), MD79257 (alkenone from marine sediment core), and Cold Air and Anjohibe&Anjokipoty caves (stalagmites $\delta^{18}O$).

4) the ITCZ is presented as the main and only driving force to explain the regional hydrological changes ignoring the Indian Ocean Dipole.

Response: There are many climate-driving mechanisms that influence climate in Madagascar. We are aware of IOD, ENSO, and other SST influences on the climate of Madagascar, but one reason we did not include such discussion in our previous discussion was because of the age uncertainty. I was hesitant to make an inference from data with age uncertainties greater than the IOD frequency (~3-7 years).

Regardless, to account for RC2's comments, we fully revised the discussion section. We shortened the discussion about the ITCZ and introduced additional discussion about the IOD. It is copied below:

5.5.Speculating on the IOD and ENSO influence on Madagascar's climate

Although the ITCZ is the main driver of rainfall availability in Madagascar, recent studies have also suggested the importance of SST changes in the surrounding ocean and teleconnection with other climatic phenomena. A 336-year coral oxygen isotope record from Ifaty, off SW Madagascar, revealed a strong Indian Ocean subtropical dipole events that were in phase with ENSO indices between AD 1880 and 1920, and between 1930 and 1940, and after 1970 in austral summers (Zinke et al., 2004). Annually laminated stalagmites from Anjohibe Cave also suggest linkages between rainfall and ENSO in Northwestern Madagascar since AD 1550 (Brook et al., 1999). Brook et al.'s review of ENSO's linkage to the climate of Madagascar (see Brook et al., 1999, p. 700) however suggests that this relationship is less clear and complicated. This complication could be associated with an unclear or yet a limited understanding of the relationship between IOD and ENSO, which is still a subject of debate (e.g. Saji et al., 1999; Li et al., 2003; Lee et al., 2008 versus Brown et al., 2009; Schott et al., 2009; Shinoda et al., 2004; Venzke et al., 2000; Abram et al., 2008; Saji and Yagamata, 2003; Meyers et al., 2007). Our understanding of the oceanic and atmospheric circulation is also challenged because IOD and ENSO share similar features in the associated SST and precipitation anomalies (e.g. Saji et al., 1999; Webster et al., 1999; Krishnamurty and Kirtman, 2003; Meyers et al., 2007). In addition, the driving mechanisms of ENSO and IOD during the Holocene are not fully understood, despite some known linkages with insolation (e.g. Otto-Bliesner et al., 2003; Liu et al., 2000; Timmermann et al., 2007; Zheng et al., 2008; Tudhope et al., 2001; Moy et al., 2002; Koutavas et al., 2006; Conroy et al., 2008;

Kuhnert et al., 2014; Liu et al., 2003; Abram et al., 2007). The IOD signals in the tropical Indian Ocean may additionally be overridden by the global mean temperature (e.g. Vecchi and Soden, 2007; Zheng et al., 2013), or the signals could be strongly influenced by monsoonal changes in the surrounding landmasses (e.g. Abram et al., 2007; Qiu et al., 2012).

Nevertheless, an evaluation of available Holocene paleoclimate records within the IOD-affected region could suggest that a long-term influence of the IOD on the climate of NW Madagascar during the mid-Holocene could be expected. We are presently challenged by the temporal and spatial resolution of available records, and the range of uncertainty of radiometric ages to fully evaluate such relationship (see for example Fig. 7 of Kunhert et al., 2014). The most immediate and relevant records to NW Madagascar consist of temperature reconstruction in the near-equatorial western Indian Ocean. Foraminiferal Mg/Ca ratios and $\delta^{18}O$, from a sediment core (GeoB12605) retrieved off northern Tanzania, suggests a prominent mid-Holocene cooler interval from 5.6 to 4.2 ka, with an average temperature decrease of ~1.3°C (Kunhert et al., 2014, p. 433). Temperature reconstruction from sediment TEX_{86} in the Mozambique Strait off the Zambezi River also suggests cooling (~0.5-0.7°C decrease in T°) since 6.5 ka BP (Schefuß et al., 2011). This cold condition could have been responsible for the dry MMHI conditions in NW Madagascar, similar to the cold-dry relationship reported in the Mentawai Islands (e.g. Abram et a., 2007).

The reconstructed surface ocean cooling in the near-equatorial western Indian Ocean, i.e. off Tanzania and off the Zambezi delta (Schefuß et al., 2011; Kunhert et al., 2014), is comparable with the surface ocean cooling in the equatorial eastern Indian Ocean (Abram et al., 2007; Abram et al., 2009). Cold intervals were estimated between ~5.5 and 4.3 ka BP and before 6.8 ka BP, with a temperature decrease of ~1.2°C (Abram et al., 2009). Cooling in the equatorial eastern Indian Ocean was attributed to positive IOD events, resulting from strong cross-equatorial winds due to strong Asian Monsoon (Abram et al., 2007; Abram et al., 2009). Such cooling was also observed on land (e.g. Griffiths et al., 2010).

The coeval cooling anomaly inferred from both eastern and western equatorial tropical Indian Ocean suggest that the mid-Holocene cooling can be a regional event. IOD could have played a role, but an expression of it in the western Indian Ocean could lead one to wonder if IOD alone is the driving mechanism of the mid-Holocene climate in the tropical Indian Ocean. The IOD expression in NW Madagascar might have been overridden by the global mean temperature (e.g. Vecchi and Soden, 2007; Zheng et al., 2013). Global temperature reconstruction of Marcott et al.

(2013) suggests cooler SH and warmer NH, and this interhemispheric difference in temperature could suggest a northward migration of the ITCZ, leading to drier conditions in NW Madagascar (this study) and in Mentawai Islands (e.g. Abram et al., 2007). This northward migration of the ITCZ might be too simple to explain the regional climate in the tropical Indian Ocean, but it could be in phase with a contraction of the Indo-Pacific Warm Pool, as proposed by Abram et al. (2009), Griffiths et al. (2010), and Yan et al. (2015). Evidence of an expansion and contraction of the ITCZ in western Indian Ocean has not yet been reported, thus hindering a full investigation of such relationship. In addition, more paleoclimate records are needed to better understand the forcings mechanism of the Holocene climate change in the tropical Indian Ocean."

Setting Describe the climatic anomalies that are observed today.

Response: We added a new section "2.3. Climate of Madagascar" in the setting, and this new section is copied below:

"The climate of Madagascar is unique because of its varied topography and its position in the Indian Ocean. Its climate has been reviewed in several recent works (e.g. Jury, 2003; DGM, 2008, Douglas and Zinke, 2015, p. 281-299; Voarintsoa et al., 2017, p.138-139). Regionally distinct rainfall gradients from east to west and from north to south, are evident across the country (Jury, 2003; Dewar and Richard, 2007). Eastern Madagascar is the rainiest and southern/southwestern Madagascar is the driest. These rainfall gradients are linked to easterly trade-winds in winter (May-October) and northwesterly tropical storms in summer, respectively. The latter has been called by the Service Météorologique of Madagascar the "Malagasy monsoon". The Malagasy monsoon is associated with the southward migration of the ITCZ, which is the main driver of austral summer rainfall in NW Madagascar, our study location.

Beyond the ITCZ, climate of Madagascar is also influenced by changes in the Indian Ocean sea surface temperatures (SST) (Zinke et al., 2004; see also Kunhert et al., 2014) and changes in SST of the adjacent current off southwestern Madagascar, the Aghulas current (Lutjeharms, 2006; Beal et al., 2011; Zinke et al., 2014). The most immediate signal is the Indian Ocean Dipole (IOD), also known as the Indian Ocean Zonal Mode (Li et al., 2003). IOD is defined as a coupled atmosphere-ocean mode in the tropical Indian Ocean (e.g. Saji et al., 1999; Webster et al., 1999; Brown et al., 2009; Yagamata et al., 2004; Behera et al., 2013). It is characterized by a reversal of the climatological SST gradient (east-west) and winds across the Indian Ocean basin (Saji et al., 1999; Webster et al., 1999; Abram et al., 2007; Brown et al., 2009). A positive IOD event starts with anomalous SST cooling along the Sumatra-Java coast in the eastern Indian Ocean, along with positive SST anomaly in the western part of the basin (e.g. Saji et al., 1999; Abram et al., 2007). Such positive IOD events are observed to result in increased precipitation, sometimes as devastating floods, over east Africa (Black et al., 2003; Saji et al., 1999; Weller and Cai, 2014). Such events have also enhanced precipitation over the northern part of India, the Bay of Bengal, Indochina, and southern part of China in 1994 (e.g. Behera et al., 1999; Guan and Yamagata, 2003; Saji and Yagamata, 2003). In the eastern Indian Ocean, positive IOD is found to intensify El-Niño related drought, often as severe droughts, over Indonesia (Webster et al., 1999; Weller and Cai, 2014). However, the relationship between IOD and El-Nino Southern Oscillation (ENSO) is still debated. While some researchers found no relationship (e.g. Saji et al., 1999; Li et al., 2003; Lee et al., 2008), others found some relationships (e.g. Brown et al., 2009; Schott et al., 2009; Shinoda et al., 2004; Venzke et al., 2000).

Beyond the coral study of Zinke et al. (2004), our knowledge about the IOD in Madagascar is still limited, specifically during the Holocene. With our current knowledge of the various climate forcing mechanism in Madagascar, this stalagmite study will help us better understand how such mechanisms could have influenced climate in Madagascar during the Holocene."

Discussion 8.2 ka: all right I can see a decrease in ∂ 18O and ∂13C . However before and after 8.2 k we observe that Âń the similar patterns as the ∂18O of Greenland Âz˙is absent. Is similarity only detected at 8.2k ?

Authors' note: We do not understand "Âń" and "Âz".

Response: To address this, we updated the presentation of the figure and indicate some other possible similarities with the Greenland records.

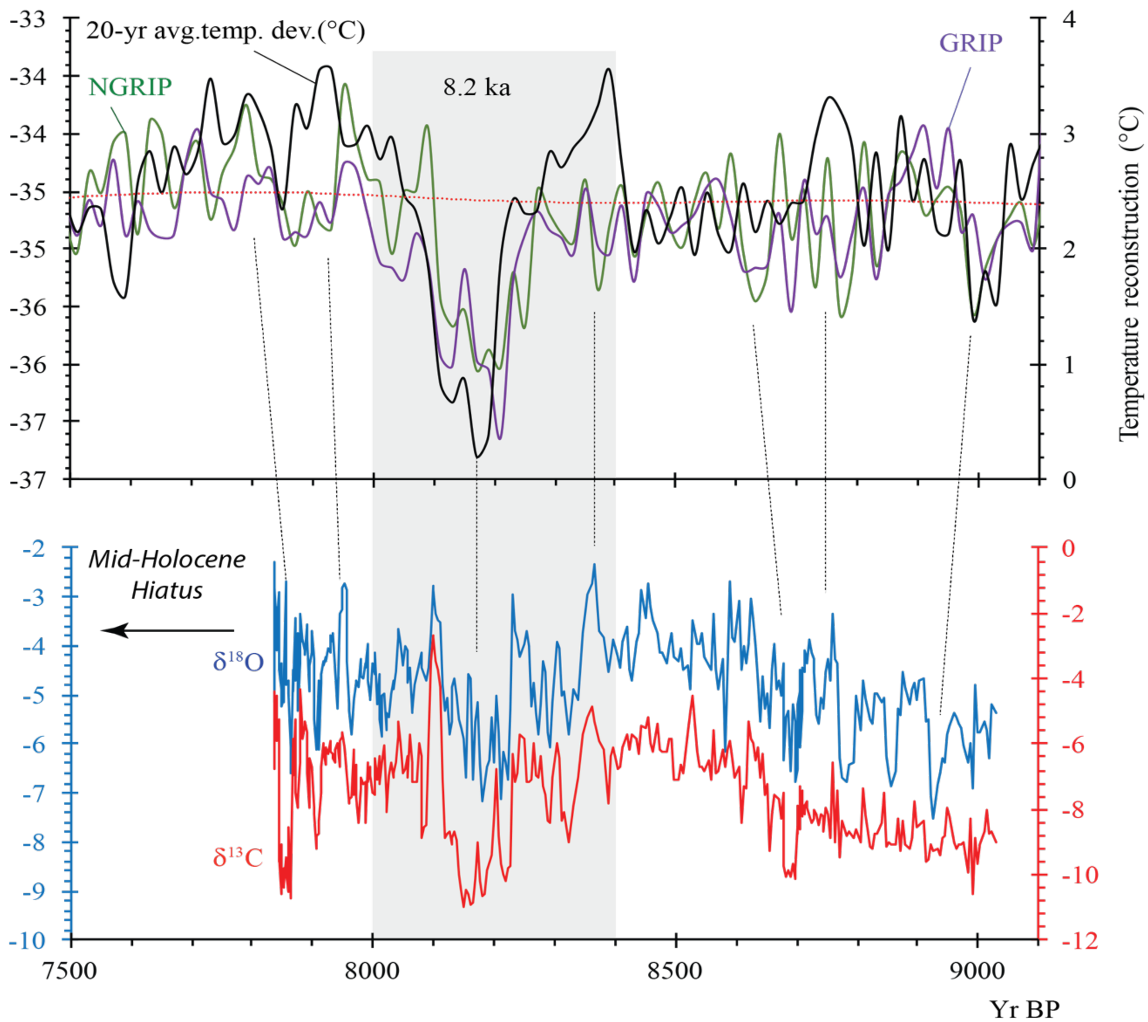

Figure__: The 8.2 ka event in Madagascar (this study) compared with the Greenland record (Vinther et al., 2009).

The discussion on ITCZ is too long and includes too many generalities nd no novelties. New scientific questions should arise at the end of the paper.

Authors' note: I am not sure about the specific "novelties" the reviewer is addressing. There are many hypotheses still to be tested in Southwestern Indian Ocean, which has already been stated in previous literatures (e.g. ITCZ, ENSO, IOD), but have not been fully tested.

Response: We indeed added relevant research questions at the concluding remark, and those questions address the ITCZ behavior (N-S migration and contraction-expansion) and IOD-ENSO influence in Madagascar. We also pointed out the need for more higher resolution records in the

SW Indian Ocean to better constrain the discrepancies and better understand the regional climate within the Indian Ocean Warm Pool.

Figures We need a map with the location of the other paleoclimate reconstructions around the Indian Ocean and Eastern Africa

Done--Please see above

Figure 5 I can see many differences between the two sites at a same age.

Figure 6 I do not understand this figure.

Response: As mentioned above, we revised several figures, including figure 5 and 6.