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Dr. Raymond Bradley
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Dear Raymond,

Thanks so much for providing editorial direction and soliciting excellent comments from two reviewers. We think this process has resulted in an improved manuscript. We used your overview as a guide and have followed through on the overwhelming majority of suggestions/comments. You can follow our point-by-point responses to reviewers' suggestions/comments, a list of changes and a marked-up manuscript (attached at the back). In the revised manuscript, we changed the title of the manuscript into 'Hydroclimatic variability in the southwestern Indian Ocean between 6000 and 3000 years ago'. Due to mismatch between "Late Holocene" in the previous title and the discussed time interval (between 6 and 3 ka BP) in the manuscript, we would like to rename it clearly to avoid confusion.

We very much appreciate your efforts, as well as those of the referees. We hope that we have satisfied the essence of the comments and suggestions.

Sincerely,

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1.Point-by-point response

Reviewer #1 from Dr. Nick Scroxton:

General Comments:

In this high-quality paper Li et al. produce a much-needed record of monsoonal variability during the middle-late Holocene from the southern hemisphere. It fills an important spatial gap in our understanding of the 4.2 kyr BP event, and an important temporal gap of the middle Holocene from the southern Indian Ocean. Given the recent announcement of the Meghalayan age, this paper is also particularly timely. The fundamental conclusion of an expanded and contracted ITCZ during the middle Holocene rather than north-south translation is well founded and an important advance. It may not provide brand new concepts or methods, but not all papers have to do so to be important, and this paper still makes a substantial contribution to progress given the spatial and temporal gaps it fills.
The paper is well presented and compact, focusing only on what's necessary, with few needless additions. It is well-written in understandable English. Altogether the writing is compact, although there may be one or two too many figures. Of recent papers I have reviewed, this one was the most enjoyable to read. I would rate it as excellent under presentation quality.

Answer- We thank the reviewer for his positive evaluation of our manuscript.

It is certainly a suitable paper for Climate of the Past. I would rate it as excellent under scientific significance. The record itself is of high-quality, with good replication from a nearby cave and a precise age model. The interpretation of the proxy is well anchored in modelled and observational data. There are a few inconsistencies within the paper (dealt with in the specific comments), but on the whole discussion of the results is balanced, without overreach. The conclusion reached, that of an expansion and contraction of ITCZ during the middle Holocene rather than north-south translation is well founded in places, but perhaps more could be done demonstrate whether this mechanism is functional throughout the entire 3000 year stalagmite growth phase rather than just a 500 year window.

Answer- Briefly, we find that the ITCZ contraction mechanism best explains the observed temporal patterns of changes in climate inferred from various proxy records only between 4.1 and 3.5 ka. We will add new text in the discussion section throughout the length of our record. Centered with the climatic variations during the 4.2 ka event (between 4.2 and 3.9 ka BP), we will discuss the main pattern of climate variation before and after 4.2 ka event.

However, I do not believe that one of the conclusions reached is supported by the data and believe there is a temporal mismatch between the interpretation, and what is going on. The authors correctly identify a drying trend that begins at 4.0 or 3.9 kyr and goes on to 3.5 kyr BP. They identify a regional coherency with other speleothem records at Liang Luar, Sahiya and possibly Tangga, and they suggest a plausible mechanism of expansion and contraction of the ITCZ range. However, they erroneously attribute this to the 4.2 kyr event (4.2 kyr BP-3.9 kyr BP) ignoring a small negative isotope excursion (wetter conditions) that exists in the new record and in the Liang Luar and Sahiya records. The regional replication of the signal and quality of the dating on this record and others is sufficient that this offset is unlikely to be due to age model errors. At this time, I would only rate the scientific quality as fair, but I do not believe much work is necessary for it to be excellent.

Answer- This is a good comment/suggestion. We did not mean to attribute the 3.9 to 3.5 ka drought to the 4.2 ka event but perhaps we did not make it clear. We will clarify the discussion in the revised text and figures.

Specific Comments:
Where does the drying start? 4.2 kyr BP as the onset of the drying trend: Line 212 you say that the 4.2kyr event marks the onset of the drying trend. You also use other records as evidence for this around line 236. 4.1 kyr BP as the onset of the drying trend: figure 9 deriving from an early d18O low 4.0 kyr BP as the onset of the drying trend: Lines 28, 204, 233, deriving from a late d18O low. Figure 8 3.9 kyr BP as the onset of the drying trend: Lines 27, 214, deriving from the change in mean state.
When using 4.1 or 4.0 you measure from the lowest low d18O value (149.2mm or 145.2mm) of one of your two stalagmites. But that doesn't necessarily mean that's the point at which the climate changes. To say drying begins at the wettest part of a wet excursion is technically correct, but misleading. That's just the wettest point of a wet period. I'd be more convinced by the point at which the mean state shifts. Tools such as Rampfit or Bayesian Change Point Analysis would identify this quantitatively, but it qualitatively looks like 3.9 kyr BP to me. In the data there is abrupt shift from d18O values between 3and 4 per mill to d18O values between 2 and 3 per mill at 140.6mm (3887 kyr BP COPRA or 3934 kyr BP ISCAM) with the d13C changing 1mm earlier at 141.6mm (3904/3964 kyr BP). This is also the point at which the mean d18O switches to dry conditions (positive z-score) in figure 6. To me. 3.9 is a more convincing point to start taking about dry periods and drought (especially as the title is about Megadrought).

Answer- We agree with the reviewer that the onset of the drying trend should be considered at a point where both $\delta^{18}O$ and $\delta^{13}C$ values increased above the long-term mean of the record. We confirmed that transition occurred ~3.9 ka BP by using change-point function in RAMPFIT (Mudelsee, 2000).

Is this the 4.2 kyr event or not? Given the age uncertainties on both the event as recorded elsewhere (maybe not great in individual records but I think the community is now pretty satisfied with 4.2 given the array of evidence) and in the stalagmite itself (excellent as expected) then 3.9-3.5 spell of dry conditions is not the 4.2-3.9kyr event. Even if you disagree with my argument above and take 4.0 as the onset of drying, I wouldn't necessarily call that coherence with 4.2 either. As you state in the abstract, the inferred hydroclimatic state over the length of the record is not distinguishable from the region's mean hydroclimate between 4.2 and 4.0 kyr BP.

Answer- The reviewer is right. As we noted in the previous response, we will refine in the revised version that the dry event between 3.9 and 3.5 ka BP is temporally a 'post-event' megadrought of the 4.2 ka event.

When you then compare the new record with others, there's a regional coherency to this weak wet and strong dry phasing. Rodrigues has a small wet excursion (likely insignificant as stated in the abstract) between 4.2 and 4.0 kyr BP. You show this explicitly in figure 8. Figure 8 also shows the Liang Luar Record with a wet excursion during this period and drying after. Tangga Cave also possibly shows this pattern too (though its more ambiguous and maybe not quite robust enough to call 'wet'). In Figure 9 you also have Sahiya cave showing a wet excursion between 4.2 and 4.0/3.9 kyr BP, and then drying after*. Three or four precisely dated speleothem records, east and west of the Indian Ocean, north and south of the equator. All showing the same thing. Slightly, but not abnormally, wet conditions (4.2-4.0 kyr BP), dry conditions (4.0-3.5 kyr BP). In which case, does this paper show how unimportant the 4.2 kyr event is in this part of the world. I think you've got a great story here, and it's not being told.
* Kathyat et al., 2017 make the same interpretation here too, analaysing the onset of peak wet conditions as the start of a drying trend, instead of interpreting a wet period followed by a dry period.
What about other parts of the record? Section 4.3 is title about patterns of hydroclimate variability between 6 and 3 kyr BP. Yet the discussion focuses only on a seven-hundredyear period (4.2-3.5 kyr BP). While the proposed mechanism is plausible for this period, is it also plausible for the other 2300 years of speleothem record? I feel this deserves more discussion.

Answer- Following the comments/suggestions, we will substantially revise our text to address most of the reviewer's comments above: we characterize the main pattern of climate variability in terms of three parts, including the pre-event, '4.2ka event' and the post-event.

Additional Comments Line 134: Any justification for choosing the standard crustal value for the initial 230/232 ratio? Stratigaphic constraints, isochrons etc.

Answer- The initial ^{230}Th correction of all dates assumes an initial ^{230}Th/^{232}Th atomic ratio of $(4.4 \pm 2.2)\times10^{-6}$ (the crustal value). We arbitrarily assigned a large uncertainty to the initial ratio, i.e., 50%. The fact that all the dates with different measured ^{230}Th/^{232}Th ratios are in stratigraphic order after corrections is consistent with the assumption for the correction. In addition, most corrections result in relatively small changes due to low ^{232}Th contents.

Line 144: Please state which age model do you end up using as your data?

Answer- We used the COPRA program to obtain our age model. We will add this information in the revised manuscript.

Line 208: Could gradual positive trends and abrupt terminations be related to drip dynamics rather than climate? A gradually drying karst storage component with rapid fill would produce this kind of shape.

Answer- We will address this comment by adding a new paragraph to discuss the possibility of the effect from the soil zone and epikarst, in addition to rainfall amount.

Line 217: On line 217 you state that the Lake Malawi record shows a weak dry excursion 4.1 – 3.5 kyr BP. On Line 254 you state that the Lake Malawi record shows virtually unchanged hydroclimate conditions. Figure 7 looks like very little change in the Lake Malawi record to me. You should probably delete the Line 217 sentence.

Answer- We agree and delete.

Line 258: I understand the desire to include brand new records in a paper, and that these sometimes have to be added last minute. But you introduce an entirely new concept (Southern Hemisphere Westerly winds and their control of restricting the southern range of the ITCZ) in the last sentence of the paper. You either need to introduce this concept much earlier or remove this record and discussion.

Answer- We agree. We will remove the discussion about the Southern Hemisphere Westerlies in the revised version.

Various: Please be consistent with how you label and refer to different records between figures and text. It makes it much harder to follow your argument when you cannot easily switch between the two. Non-speleothem experts who do not know which country relates to which specific cave name and which specific stalagmite in that cave will find it difficult to keep track Line 215: Tatos Basin in text, Mauritius in figure 7 Line 220: Sumatra in text, Tangga cave in figure 8 Line 220: Northwest Australia in text, KNI-51 in figure 8.

Answer- We will uniform the names.

Figures: 9 figures is a lot for a short paper such as this. Could figures 8 and 9 be combined given they essentially show the same thing – i.e. regional coherency.

Answer- According to reviewer's suggestion, we will move the previous Figures 2 to 5 to supplementary materials to reduce the number of figures in the main text. We will also combine the previous Figures 7 and 9 into one figure, i.e., Figure 5 in the revised manuscript.

Technical Corrections Line 119: No need to use respectively twice in consecutive sentences. Line 142: Spell out ISCAM at first usage. Line 172: No need to spell out ISCAM at second usage. Line 166: The Dorale and Liu test is even more convincing when consistent between two nearby caves, you should state this more explicitly that "speleothems from the same cave" Line 173: In line 70, you state PATA1 stops growing at 3.5 kyr BP. In line 173 you have overlap between the two stalagmites up to 3.4 kyr BP. Line 317: Th in superscript Line 349: Blank line? Figure 1: Coastlines should be in a darker color to make them clearer Figure 1: You should show the isohyet on the scale bar Line 497: 199?
Answer- We agree and will correct in the revised version.

Reviewer #2:

Climate of the Past Submission **cp-2018-100,** "Speleothem Evidence for Megadroughts in the SW Indian Ocean during the Late Holocene" by Li et al., presents evidence from two stalagmites from Rodrigues Island in the southwestern Indian Ocean and makes inferences about climate from 4500 to 3000 years BP. The most profound inference is of a "multicentennial period of drought (i.e., megadrought) that lasted continuously from ~ 3.9 to 3.5 ka BP".

The fundamentals of this kind of research are

(A) the stalagmite(s) studied,

(B) the radiometric ages,

(C) the age model resulting from A and B,

(D) the data placed in time-series using C, and

(E) the reasoning employed to interpret the data in D.

I will therefore proceed through this list and then consider the broader implications of the manuscript. This leads to six enumerated suggestions for improvement of the manuscript. A figure on the second page illustrates some of the points made.

A. The stalagmites studied

The study draws on two stalagmites, LAVI-4 and PATA-1, from two caves on Rodrigues Island. I *infer* from Figure 4B that the project does not draw on the entirety of Stalagmite PATA-1. As I said, I had to *infer* this, and I do not see it stated in the text. I think it should be, to save readers confusion, and hence my first suggestion:

Suggestion 1. The manuscript and its figures should make explicit what portions of the two stalagmites were analyzed for this project.

Answer- We agree. We will add explicit descriptions about the portions of the two stalagmite that we used in this study. We will clearly mark the portions of the two samples using blue bars in the related figure.

The images of the stalagmites provided in Figure 4 suggest that significant layerbounding surfaces (Railsback et al., 2013) may be present, but no mention of layer-bounding surfaces is made in the text, leaving the reader to wonder if the authors infer none or, alternately, did not look for them. This leads me to Suggestion 2.

Suggestion 2: The manuscript should report the layer-bounding surfaces seen in the stalagmite or state explicitly that there are none.

Both of these suggestions will matter considerably later.

Answer- Thanks for the suggestion. Railsback et al. (2013) identified two types of layer-bounding surfaces in their stalagmite: Type E, formed under wet conditions and Type L reflecting dry conditions. Upon a closer petrographic inspection, type L surface likely occurred at ~124 mm depth in stalagmite LAVI-4.

B. Radiometric ages

The manuscript focuses on the period from 4500 to 3000 years BP (ostensibly around 4.0 ka for the "4.2 ka BP event", but the big result comes later in the 3000s years BP). The number of ages reported is as follows:

Stalagmite Number of ages between 4500 and 3000 BP

LAVI-4	16
PATA-1	**1**

LAVI-4 is clearly thoroughly dated, but PATA-1 has only one age in the time interval of interest. This will be important in Part C and will lead to Suggestion 3.

Answer- In order to improve the age model for sample PATA-1 we have obtained two additional ^{230}Th dates between 4 and 4.5 ka BP. The new subsamples of PATA-1 were drilled at 20 mm (4284 ±87 years BP) and 22.2 mm (4494 ±138 years BP), respectively. The reconstructed age model with new additional dates is consistent with the previous one, but more robust.

C. Age models

C1: The PATA-1 age model

Through the time interval of interest, the age model for PATA-1 in Figure 4B is a straight line, and the very quantitative algorithms used to generate the age models give relatively small uncertainties. However, the age of material from 18 to 24 mm from the top is unconstrained because there are no radiometric ages in that interval. Application of growth rates derived from earlier parts of the stalagmite (my dashed lines on Figure 4B) suggests that the material at 22 mm from the top could be anywhere from 4600 to 3900 years old (and a hiatus could make the range even greater).

To summarize Section B and the previous paragraph, because the PATA-1 record from 4.6 to 3.6 ka has only one U-series date, age is largely unconstrained in that interval. Thus PATA-1 provides an isotopic record correlative with that of LAVI-4, but PATA-1 is of no help with chronology. This leads me to Suggestion 3.

Suggestion 3. The statements that the manuscript presents “chronologically well-constrained speleothem oxygen and carbon isotopes record**s** of hydroclimate” (Lines 23 and 24) and “**two** precisely dated speleothem oxygen (δ18O) and carbon (δ13C) isotope record**s**” (Line 67) should be changed to the singular “record”, and the word “two” should be deleted, because the manuscript in fact presents only one chronologically well-constrained record of the interval of interest, not two. The plural claim “record**s** have tight age control” is likewise invalidated.

Answer- We agree with the reviewer. As we noted in the previous response, we have added two additional dates for PATA-1. We will refine the statements in the revised version.

C2: The LAVI-4 age model

The LAVI-4 age model in Figure 4A presents the results of many radiometric analyses, which is good. Figure 4A suggests a relatively constant rate of growth, with one exception about which three points can be made:

a) Growth is relatively constant except at 123 mm, where the growth rate is much less, suggestive of a hiatus.

b) The image of stalagmite nested in Figure 4A (the only image provided) is not particularly clear, and the indexing scheme is not shown, but my attempt to reconstruct the indexing to which readers are not privy suggests that there may be a layer-bounding surface (and thus a possible hiatus) at about 123 mm.

c) In the stable isotope data from about 123 mm, there is a shift in δ13C of about 6.2‰ between two successive stable isotope samples. The manuscript says that resolution of the data is about 4 years, so that the data imply a change in δ13C of about 6.2‰ over about 4 years. That implies a major ecosystem shift and shift in soil carbon (which has decades-to-centuries residence times) in just four years. A more likely explanation is a hiatus in which the unrecorded time allowed the shift in soil ecology at feasible rates. Points a, b, and c lead to Suggestion 4.

Suggestion 4. Either the manuscript should be revised to use an age model including the hiatus evident at about 123 mm, or the manuscript should explicitly explain why it rejects the hiatus that will be evident to many readers. Clearly the statement in Lines 120 to 121 that "both samples grew continuously between 3.5 and 6.0 ka BP interval without any visible hiatuses" should be reconsidered.

As an aside, I would add that the problem here is a common result of generation of age models using computer programs that are not written to include hiatuses and that do not consider evidence beyond the radiometric dates. Use of these programs seems very quantitative and objective, so it is attractive, but it also leads to non-recognition of hiatuses and thus flawed age models. It is far better to recognize a hiatus, to generate a better age model, and to interpret the cause of the hiatus – and in this case the hiatus is very convincing evidence of extremely dry conditions.

Answer- Good point again. We will add a figure to show two possibilities for the sample LAVI-4 at a depth of ~124 mm, a hiatus (~100 years) as suggested by the reviewer, or a portion of the sample with a very slow growth rate. Either way, the major hydroclimatic patterns between 6 and 3 ka BP inferred from our records, thus our conclusions, remain similar.

D. Stable isotope data

The manuscript reports both δ18O and δ13C data, which is good – some researchers oddly do not report their δ13C data, despite its usefulness. The data reported seem quite normal: range of δ13C is greater than that of δ18O, both are in the negative single-digit values (relative to VPDB) typical of stalagmites, etc. The two co-vary, which is typical of settings in which rainfall limits the extent of vegetation. LAVI-4 has greater ranges of both δ13C and δ18O than PATA-1.

One notable omission is that the stable isotope data from PATA-1 stop at 15 mm below the top of the stalagmite, during the most extreme part of the "megadrought", and do not record the return to the less extreme conditions. This is like reading a novel only to find the last few pages have been torn out. Definition of the time and duration of the megadrought would seemingly require continuation of the PATA-1 series of stable isotope data later above 15 mm from the top of the stalagmite.

Note that the unexplained absence of data from above 15 mm in PATA-1 invalidates the abstract's claim to "present high-resolution and chronologically well-constrained speleothem oxygen and carbon isotopes records of hydroclimate variability **between ~6 and 3 ka ago** from Rodrigues Island": PATA-1 was not analyzed to give a record after 3.5 ka.

Suggestion 5: The PATA-1 series of stable isotope data should be extended higher/later than its present extent, or the manuscript should explain the omission to readers who wonder why it was terminated in mid-event. If the omission persists, the abstract's claim to "record**s** [plural] of hydroclimate variability between ~6 and 3 ka ago" should be modified, because only one record goes to 3 ka.

Answer- Sample PATA-1 shows a major hiatus at 15 mm. Based on our dating results, growth re-commenced after ~630 years at ~2740 yr BP. Thus, the record of the top 15 mm may not be helpful for the issues we addressed here. We will add this information in the revised manuscript.

E. Reasoning employed to interpret the data

Lines 105 to 109 lay out the mindset used to interpret the oxygen isotope data, which hinges entirely on the amount effect giving an inverse relationship between δ18O and rainfall. I know little about the Indian Ocean but find no problem with that general assumption, but there is a growing literature suggesting that post-rainfall effects like evaporation are important too. No literature is cited in the manuscript. McDermott (2004) and Lachniet (2009) commonly are cited with regard to the amount effect and Cuthbert et al. (2014), Markowska et al. (2016), and Treble et al. (2017) are examples of the newer literature.
The rationalization of the carbon isotope data appears much later, in Lines 190 to 195, and similarly seems sound.

Answer- According to this suggestion, we will add a paragraph to discuss the effect of prior evaporation process in changing the composition of drip-water $\delta^{18}O$ in the shallow soil zone and epikarst. We will also cite the relevant papers, including those suggested by the reviewer.

Broader considerations

The 4.2 ka BP event is prominent in the abstract and introduction, but it hardly gets a mention thereafter. The former, rather than the latter, seems strange, because the present manuscript is mostly concerned with a major dry event that happened later, at 3.9 to 3.5 ka. Lines 209 to 211 in fact disavow any recognition of the 4.2 ka BP event, stating the "the interval corresponding to the '4.2 ka event', typically considered between 4.2 and 3.9 ka BP (e.g., Weiss et al., 2016), in the LAVI-4 records does not however, stand out as 'pulse-like' event as evident in many other proxy records". One thus has to wonder why all the mention of the 4.2 ka BP event in the abstract and introduction.
With that said, one can return to the LAVI-4 data in which age is well constrained and see two negative/wet spikes in δ18O in the interval from 4.15 to 3.93 ka (see my mark-up figure). Railsback et al. (2018) concluded that the so-called 4.2 ka BP event took place from 4.15 to 3.93 ka, commonly is recognized as two pulses, and in Namibia can be recognized as two moderately wet pulses. That's exactly what can be seen in LAVI-4.This leads to Suggestion 6:
Suggestion 6: Either the manuscript's presently incongruous early focus on the so-called 4.2 ka BP event should be de-emphasized, most notably in the abstract, or the manuscript should discuss the project's data about the 4.2 ka BP event, which suggest a pair of wet pulses congruent with other published data from the Southern Hemisphere's zone of summer rainfall.

Answer- We addressed this comment by keeping the focus on the 4.2 ka event and using the record before and after the event to provide a climatic context for the event. First, we agree with the reviewer. In the revised manuscript, we will characterize the wet and dry events during the 4.2 ka event (4.2 to 3.9 ka BP), and discuss its correlation with other well-dated records (e.g., the Dante cave record (Railsback et al., 2018)). Then we will point out that the multi-decadal fluctuations during the 4.2 ka event are similar to those in the time period from 6 to 4.2 ka BP with a mean state of our entire record between 6 and 3 ka BP. Third, we'll characterize the aridity between 3.9 and 3.5 ka BP as a 'post-event' megadrought. Thus, our data provide new insights not only into the climatic variability during the 4.2 ka event, but also broader background information surrounding the event.

Minor things

a) In Line 177, PATA1 should be PATA-1 b) de Boer et al. (2013, 2014, 2015) are listed in the references as "Boer", E.J.D., 2013 . . .", which left this reader scrambling. c) Edwards et al. (1987) is between the Cs and Ds in the references.

Answer- We agree. We will fix these in the revised manuscript.

2. A list of changes

1) We add explicit descriptions about the portions of the two stalagmite that we used in this study. (Lines 153-154 and 159 in Page 4) We clearly mark the portions of the two samples using blue bars in the Supplementary Fig.3.

2) We add the layer-boundary and related age-model discussion for LAVI-4 at 124mm. (Lines 155-158 in Page 4)

3) We add two additional dates for PATA-1 and update its age-model. We clarify a hiatus of PATA-1 occurred around 15 mm. (Lines 159-160 in Page 4)

4) We clarify that we use COPPRA result for further discussion. (Lines 161-162 in Page4)

5) We add the discussion about the effect from the soil zone and epikarst and cite the references mentioned by the reviewer. (Lines 195-202 in Page 5)

6) We clarify the climate variation pattern in terms of pre-event, '4.2 ka event' and post-event between 6000 and 3000yr BP. (Lines 210-213, 217-219 and 225-232 in Page 6)

7) We remove the statement saying that Lake Malawi record shows a weak dry excursion.

8) We remove the discussion about Southern Hemisphere Westerlies.

9) We uniform the names in the text and graphs. (e.g.: Lines 233-238 in Page 6 and Fig.4)

10) We change previous Fig.5 to Fig.2, change previous Fig. 6 to Fig.3, change previous Fig. 8 to Fig. 4 and combine previous Figs. 7 and 9 into Fig. 5. We move the previous Figures 2 to 4 to supplementary materials.

3. A marked-up manuscript

Hydroclimatic variability in the southwestern Indian Ocean between 6000 and 3000 years ago

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Abstract

The '4.2 ka event' is frequently described as a major global climate anomaly between 4.2 and 3.9 ka BP, which defines the beginning of the current Meghalayan age in the Holocene epoch. The 'event' has been disproportionately reported from proxy records from Northern Hemisphere but its climatic manifestation remains much less clear in Southern Hemisphere. Here, we present highly resolved and chronologically well-constrained speleothem oxygen and carbon isotopes records between ~6 and 3 ka BP from Rodrigues Island in the southwestern subtropical Indian Ocean, located ~600 km east of Mauritius. Our records show that the '4.2 ka event' did not manifest as a period of major climate change at Rodrigues Island in the context of our record's length. Instead, we find evidence for a multi-centennial drought that occurred near-continuously between 3.9 and 3.5 ka BP and temporally coincided with climate change throughout the Southern Hemisphere.

1. Introduction

The '4.2 ka event' is considered as a widespread climate event between 4.2 and 3.9 ka BP (thousand years before present, where present = 1950 AD) (e.g., Weiss et al., 1993, 2016). Many paleoclimate records from the Northern Hemisphere (NH) have characterized the event as a multi-decadal to multi-centennial period of arid and cooler conditions across the Mediterranean, Middle East, South Asia and North Africa (e.g., Finné et al., 2011; Marchant and Hooghiemstra, 2004; Migowski et al., 2006; Mayewski et al., 2004; Staubwasser et al., 2003; Arz et al., 2006; Zielhofer et al., 2017; Stanley et al., 2003; Kathayat et al., 2017). The structure of the '4.2 ka event' from many proxy records such as peat cellulose records from the eastern Tibetan Plateau (Hong et al., 2003, 2018), speleothem from northeastern India (Berkelhammer et al., 2012) and southern Italy (Drysdale et al., 2006), marine sediments from the Gulf of Oman (Cullen et al., 2000) and the northern Red Sea (Arz et al., 2006), and the dust record in the Kilimanjaro ice core (Thompson et al., 2002) typically characterized it as a single pulse-like signal in the long term context of these records. In contrast, the structure of '4.2 ka event' in Southern Hemisphere (SH) remains unclear. Some proxy records from the tropical and sub-tropical regions of Africa and Australia show a shift towards drier conditions around 4 ka BP (e.g., Russell et al., 2003; Marchant and Hooghiemstra, 2004; Griffiths et al., 2009; Denniston et al., 2013; Berke et al., 2012; De Boer et al., 2013, 2014, 2015; Schefuβ et al., 2011; Rijsdijk et al., 2009, 2011). Other records show virtually unchanged hydrological conditions (e.g., Tierney et al., 2008, 2011; Konecky et al., 2011) or a two-pulsed multi-decadal length wet events (Railsback et al., 2018) during the period contemporaneous with the 4.2 ka event.

The goal of this study is to investigate the '4.2 ka event' in a key region of the SH via highly resolved and precisely dated proxy records. Here, we present speleothem oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotope records from La Vierge (LAVI-4) and Patate (PATA-1) caves from the Rodrigues Island (Fig.1) in the southern subtropical Indian Ocean. The LAVI-4 and PATA-1 records span from ~6 to 3 ka BP and from ~6.1 to 3.3 ka BP, with an average resolution of ~4 and 14 years, respectively. The LAVI-4, which constitutes our primary record, has a precise age control and a sub-decadal resolution, which, together with PATA-1 record, allows us to reliably characterize the multi-decadal to centennial hydroclimate variations in the southwestern Indian Ocean during the period from 6 to 3 ka BP.

2 Modern climatology

2.1 Climatology

Rodrigues (~19°42'S, ~63°24'E) is a small volcanic island (~120 km^2) situated in the southwestern Indian Ocean, ~600 km east of Mauritius (Fig. 1). The island's maximum altitude is ~400 m above sea level. Rodrigues' mean annual temperature is ~24°C and the mean annual rainfall is ~1010 mm, of which nearly 70% occurs during the wet season (November to April) with February being the wettest month. The seasonal distribution of rainfall is largely controlled by the seasonal migration of the ITCZ and the Mascarene High (Senapathi et al., 2010; Rijsdijk et al., 2011; Morioka et al., 2015) (Fig. 1). Given its location at the southern fringe of the ITCZ, the austral summer rainfall at Rodrigues is very sensitive to the mean position of the southern limit of the ITCZ. This is highlighted by backward (120 hours) HYSPLIT (Draxler and Hess, 1998) trajectory composites of the low-level winds (850 hPa) during the years when the total January to March (JFM) precipitation was unusally low (dry) and high (wet) than the long-term mean (1951-2016) at Rodrigues (Fig. 1B). Of note is a major increase in the fraction of air parcel trajectories arriving from the north of Rodrigues during the wetter years, indicating an enhanced contribution of northerly moisture resulting from a more southerly position of the ITCZ (Fig. 1B). This observation is further supported by analyses of the low-level wind trajectory cluster composites of February in those years when the southern boundary of the the ITCZ was anomolously north or south (Lashkari et al., 2017; Freitas et al., 2017) of its long-term mean February position (Supplementary Fig. 1 A-B). In addition to the ITCZ, ENSO also modulates austral summer precipiation at Rodrigues via modulating the Hadley and Walker circulations (Senapathi et al., 2010; De Boer et al., 2014; Griffiths et al., 2016; Zinke et al., 2016). Instrumental data and our trajectory composites for selected El Niño and La Niña years suggest that an increased (decreased) summer precipitation at Rodrigues is associated with the El Niño (La Niña) events (Supplementary Fig. 1C-D).

2.2 Oxygen isotopes and climatology

Modern observations of $\delta^{18}O$ of precipitation ($\delta^{18}O_P$) in the study area are unavailable due to the lack of Global Network of Isotopes in Precipitation (GNIP) stations in Rodrigues. However, $\delta^{18}O_P$ data from the nearest GNIP station in Mauritius show a clear annual cycle in $\delta^{18}O_P$ with depleted values during the austral summer (Supplementary Fig. 2A). Additionally, in the absence of GNIP data, we use simulated $\delta^{18}O_P$ data from the Experimental Climate Prediction Center's Isotope-incorporated Global Spectral Model (IsoGSM) (Yoshimura et al., 2008) to assess the large-scale dynamical processes that control $\delta^{18}O_P$ on interannual and decadal timescales. Our analyses show the presence of a strong negative correlation between the $\delta^{18}O_P$ and rainfall amount similar to the 'amount effect' (e.g., Dansgaard, 1964) (Supplementary Fig. 2B-C). We therefore interpret $\delta^{18}O_P$ variations in the cave catchment and, consequently, in speleothems from this region primarily reflecting variations in rainfall amount in response to both local and large-scale atmospheric circulation changes. The relationship is such that more negative (positive) $\delta^{18}O_P$ values occur during times of either an anomalously southward (northward) position of the southern boundary of the ITCZ or El Niño (La Niña) conditions.

3 Methods

3.1 Speleothem samples

Two stalagmites, LAVI-4 and PATA-1, from La Vierge and Patate caves, respectively, were used in this study. La Vierge (19°45′26″S, 63°22′13″E, ~32 m asl) and Patate (19°45′30″S, 63°23′11″E, ~20 m asl) caves are located in Plaine Corail and Plaine Caverne, respectively, in southwestern Rodrigues (Middleton and David, 2013). The cave temperature and relative humidity at the time of sample collection (June 2015) were ~25.5°C and 95% in La Vierge cave and ~22.5°C and 95% in Patate cave. Samples LAVI-4 and PATA-1 were collected at the distance of ~50 m and 200 m from cave entrances, respectively. The diameters of LAVI-4 and PATA-1 are ~75 and 95 mm, and their lengths are ~400 and ~334 mm, respectively. Both stalagmites were cut along their growth axes using a thin diamond blade and then polished.

3.2 ^{230}Th dating

Subsamples (80-130 mg) for ^{230}Th dating were drilled using a 0.9 mm carbide dental drill. ^{230}Th dating was performed at Xi'an Jiaotong University, China, by using a Thermo-Finnigan Neptune *plus* multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS). The method is described in Cheng et al. (2000, 2013). We used standard chemistry procedures (Edwards et al., 1987) to separate U and Th. A triple-spike (^{229}Th–^{233}U–^{236}U) isotope dilution method was used to correct instrumental fractionation and to determine U/Th isotopic ratios and concentrations (Cheng et al., 2000, 2013). U and Th isotopes were measured on a MasCom multiplier behind the retarding potential quadrupole in the peak-jumping mode using standard procedures (Cheng et al., 2000). Uncertainties in U and Th isotopic measurements were calculated offline at the 2σ level, including corrections for blanks, multiplier dark noise, abundance sensitivity, and contents of the same nuclides in the spike solution. ^{234}U and ^{230}Th decay constants of Cheng et al. (2013) were used. Corrected ^{230}Th ages assume an initial ^{230}Th/^{232}Th atomic ratio of (4.4 ±2.2)×10^{-6}, and the value for material at secular equilibrium with the bulk earth ^{232}Th/^{238}U value of 3.8. The correction for a few samples LAVI-4 and PATA-1 are large, because either U concentration is low (~65 ppb) and/or the detrital ^{232}Th concentration is elevated (>100 ppt) (Table S1, Fig. 2).

3.3 Stable isotope analysis

LAVI-4 and PATA-1 stable isotope (δ^{18}O and δ^{13}C) records were established by ~952 and ~192 data, respectively. The New Wave Micromill, a digitally controlled tri-axial micromill equipment, was used to obtain subsamples. The subsamples (~80 μg) were continuously micromilled along the stalagmites growth axes of LAVI-4 and PATA-1 at increments between 100 and 200 μm. The subsamples of LAVI-4 were measured using a Finnigan MAT-253 mass spectrometer coupled with an on-line carbonate preparation system (Kiel-IV) in the Isotope Laboratory, Xi'an Jiaotong University. The subsamples of PATA-1 were measured using an on-line carbonate preparation system (Gasbench Ⅱ) connected to an isotope ratio mass spectrometer (Delta^{plus}XL) in the Isotope Laboratory, Innsbruck University. The latter technique is reported in Spötl (2011) and Spötl and Vennemann (2003). All results are reported in per mil (‰) relative to the Vienna PeeDee Belemnite (VPDB) standard. Duplicate measurements of standards show a long-term reproducibility of ~0.1‰ (1σ) or better (Table S2, Fig. 2).

4 Results

4.1 Age models

We obtained 26 and 7 ^{230}Th dates for samples LAVI-4 and PATA-1, respectively. The LAVI-4 and PATA-1 age models and associated uncertainties were constructed using COPRA (Constructing Proxy Records from Age) (Breitenbach et al., 2012) and ISCAM (Intra-Site Correlation Age Modelling) (Fohlmeister, 2012) age modelling schemes (Supplementary Fig. 3). Both schemes yielded virtually identical age models, and thus the conclusions of this study are not sensitive to the choice of the age model (Fig. 2 and Supplementary Fig. 3).

The time interval from 6 to 3 ka BP in LAVI-4 speleothem corresponds to a sample depth of 274 to 81 mm below the top, respectively. A drip-water relocation occurred at a depth of 124 mm, which is associated with a Type L surface characterized by slow growth and narrow layers under progressively drier conditions (Railsback et al., 2013) (Supplementary Figs. 3 and 4). It cannot be ruled out that there also exists a hiatus at this depth (~3.5 ka BP). If such a hiatus was indeed present, its duration would be about 100 years based on the age model (Supplementary Fig. 4). The time interval from 6.1 to 3.3 ka BP in PATA-1 corresponds to a sample depth of 34 to 15 mm. Growth of PATA-1 ceased at ~15 mm and then resumed about 630 years later, creating a hiatus (Supplementary Fig. 3). The COPRA age models of PATA-1 and LAVI-4 (Fig. 2 and Supplementary Fig. 3) are reported in Table S2 and used in the following discussion.

4.2 Isotopic equilibrium tests

Conventional criteria to assess isotopic equilibrium of stalagmites are provided by the Hendy Test (Hendy, 1971), which requires no correlation between δ^{18}O and δ^{13}C values measured along the growth axis as well as along the same growth lamina. The correlation between the δ^{18}O and δ^{13}C values in LAVI-4 and PATA-1 is 0.53 and 0.85, respectively, which suggests the possibility of isotopic disequilibrium during calcite precipitation. However, a number of studies (e.g., Dorale and Liu, 2009) pointed out that a correlation between δ^{18}O and δ^{13}C values does not automatically rule out isotopic equilibrium. Instead, the replication test (i.e., a high degree of coherence between δ^{18}O profiles of individual speleothems from the same cave) is a more rigorous and reliable test of isotopic equilibrium. Particularly, the replication test is far more robust if the records used are from different caves with different kinetic/vadose-zone processes, such is the case for this study. Indeed, a high degree of visual similarity between the coeval portions of LAVI-4 and PATA-1 δ^{18}O and δ^{13}C records suggest that both stalagmites record primary climate signals, notwithstanding the offsets between the absolute values (Fig. 2A). The replication is further confirmed by statistically significant correlations between the LAVI-4 and PATA-1 δ^{18}O ($r = 0.64$ at 95% confidence level) and δ^{13}C ($r = 0.73$ at 95% confidence level) records calculated using the ISCAM algorithm (Fohlmeister, 2012) for their contemporary growth period between 3.4 and 6.0 ka BP (Fig. 2). ISCAM uses a Monte Carlo approach to find the best correlation between the proxy records by adjusting each record within its dating uncertainty. The significant levels are assessed against a red-noise background generated using artificially simulated first-order autoregressive time series (AR1). The offset in absolute $\delta^{18}O$ values between LAVI-4 and PATA-1, however, remains unclear, and possibly arises from processes related to the characteristics of the two karst system, such as temperature differences as observed during our fieldwork in 2015. Therefore, in the following discussion we focus only on temporal variations of LAVI-4 $\delta^{18}O$ and $\delta^{13}C$ records due to their higher resolution and better constrained chronology (Fig. 2).

5 Discussion and Conclusions

5.1 Proxy interpretation

The temporal resolution of the LAVI-4 $\delta^{18}O$ record between 6 and 3 ka BP varies from 1.2 to 16.4 years with an average resolution of ~3.2 years. The $\delta^{18}O$ temporal variability is large (~3.5 ‰) and, as noted earlier, we interpret the $\delta^{18}O$ variations to dominantly reflect changes in the precipitation amount. This line of reasoning is justified given the island's isolated setting far removed from large-sized landmasses and its low topographic relief, which minimizes isotopic variability stemming from processes such as the continentality and altitude effects as well as mixing of distant water vapor sources with significantly different isotopic compositions. This interpretation is additionally supported by moderate to strong covariance between the LAVI-4 $\delta^{18}O$ and $\delta^{13}C$ profiles. Although the process of stalagmite precipitation may be affected by evaporation and/or degassing (Treble et al., 2017; Cuthbert et al., 2014; Markowska et al., 2016; McDermott, 2004; Lachniet, 2009), the temporal variations in the latter can stem from changes in vegetation type and density, soil microbial productivity, prior calcite precipitation (PCP) and groundwater infiltration rates (e.g., Baker et al., 1997; Genty et al., 2003), all of which may drive $\delta^{18}O$ and $\delta^{13}C$ values in the same fashion (e.g., Brook et al., 1990; Dorale et al., 1992; Bar-Matthews et al., 1997). The significant covariance between the $\delta^{13}C$ and $\delta^{18}O$ records could therefore, indicate that both proxies reflect a common response to changes in rainfall amount at Rodrigues, or a rainfall limit on the extent of vegetation and other related processes in the epikarst as mentioned above.

5.2 Hydroclimate variability between 6 and 3 ka BP at Rodrigues

The z-score transformed profiles of LAVI-4 $\delta^{18}O$ and $\delta^{13}C$ records reveal several decadal to multi-decadal intervals of significantly drier and wetter conditions (> ±1 standard deviation) (Fig. 3) but no distinct long-term trends (Figs. 2 and 3). The interval corresponding to the '4.2 ka event' in the LAVI-4 $\delta^{18}O$ record, typically between 4.2 and 3.9 ka BP (e.g., Weiss et al., 2016), includes two dry (~4200 to 4130 yr. BP and ~4020 to 3975 yr. BP) and two wet (~4130 to 4020 yr. BP and ~3975 to 3945 yr. BP) periods (Fig. 3). During this time interval the LAVI-4 $\delta^{13}C$ record shows two wet periods peaking at ~4115 and 4015 yr BP, respectively, which correlate within age uncertainties with two wet pulses in proxy records from Mawmluh cave (Kathayat et al., 2018), Tangga cave (Wurtzel et al., 2018), Makassar Strait (Tierney et al., 2012), Liang Luar cave (Griffiths et al., 2009), KNI-51 cave (Denniston et al., 2013) and Dante cave (Railsback et al., 2018) (Fig. 4).

Overall, the climate variations recorded at Rodrigues from 4.2 to 3.9 ka BP are characterized by high-frequency (decadal to multi-decadal) fluctuations, including the major arid/wet events mentioned above. Notably, however, the mean hydroclimatic state of this time interval inferred from both $\delta^{18}O$ and $\delta^{13}C$ data is indistinguishable from the average state between 6 and 4.2 ka BP (Fig. 3). In this regard, the 4.2 ka event does not appear to be a strong 'single pulse-like' signal in Rodrigues in the context of the long-term climate variance between 6 and 3 ka BP. Consistently, the climatic events or anomalies between 4.2 and 3.9 ka BP are not distinctly larger in amplitude nor longer in duration in comparison to similar anomalies between 6 and 4.2 ka BP (Figs. 3 and 4).

The most prominent feature of our record is a switch from an interval characterized by high-frequency $\delta^{18}O$ variance (i.e., from 6 to 3.9 ka BP) to a multi-centennial excursion with progressively higher $\delta^{18}O$ and $\delta^{13}C$ values: a prolonged megadrought at Rodrigues. Starting at ~3.9 ka BP, this megadrought became progressively more severe leading to a diminished growth rate or a ~100 yr-long hiatus around 3.5 ka BP in LAVI-4. Growth rate picked up subsequently, followed by abrupt (~100 yr-long) and large decreases in both $\delta^{18}O$ (~2‰) and $\delta^{13}C$ (~5‰) to their average values of the entire records between 6 and 3 ka BP. As such, the structure of the megadrought event shows a saw-tooth pattern with a multi-centennial drying trend followed by a ~100 yr long return to the mean state (Fig. 3). The multi-century megadrought recorded by our stalagmites between 3.9 and 3.5 ka BP is also evident in Sahiya cave, north India (Kathayat et al., 2017), and from Lake Edward (Russell et al., 2003), Lake Victoria (Berke et al., 2012), the Zambezi delta (Schefuß et al., 2011) and the Tatos basin (De Boer et al., 2014) (Fig. 5). In the eastern sector of the southern Indian Ocean, speleothem records from Tangga (Wurtzel et al., 2018), KNI-51 (Denniston et al., 2013), and Liang Luar (Griffiths et al., 2009) caves also show a shift to drier condition at approximately 4 ka BP (Fig. 4).

The LAVI-4 $\delta^{13}C$ record shows a pattern broadly similar to the $\delta^{18}O$ record and clearly delineates three major droughts between 6 and 3 ka BP, centered at 5.43, 4.62 and 3.54 ka BP respectively. These three drought events share a distinct saw-tooth pattern characterized by a long-term gradual positive excursion (drying) followed by an abrupt return to the mean values (Fig. 3).

To sum, our Rodrigues records show evidence of multidecadal-decadal hydroclimate fluctuations around the mean state between 6 and 3 ka BP. After 3.9 ka BP, the hydroclimate was characterized by a multi-centennial trend toward much drier conditions which ended with a return at ~3.5 ka BP within ~100 years to the mean hydroclimate state. This pattern is different from the 'pulse-like' event between 4.2 and 3.9 ka BP as documented in many other proxy records mainly from the NH. Additionally, the megadrought between 3.9 and 3.5 ka BP is clearly a later event unrelated to the 4.2 ka event.

5.3 Possible mechanisms

The driving mechanisms of the 4.2 ka event remain elusive. For example, there is no clear evidence of rapid freshwater injection into the North Atlantic Ocean that could have disrupted the Atlantic meridional overturning circulation (AMOC), and thereby, produced changes in global climate in a manner akin to the 8.2 ka BP event (e.g., Cheng et al., 2009; Walker et al., 2012). There is

also no evidence of major perturbations in atmospheric concentrations of aerosols and CO_2 at this time (Monnin et al., 2001). A southward shift of the mean position of the ITCZ during this time has been hypothesized (e.g., Mayewski et al., 2004), which potentially could account for the low-latitude aridity observed in many NH locations, but this hypothesis is inconsistent with proxy records situated at the southern margin of the ITCZ in the SH, which show little or no evidence of presumably wetter conditions resulting from a southward shift of the ITCZ (e.g., Russell et al., 2003; De Boer et al., 2013, 2014, 2015; Rijsdijk et al., 2009, 2011; Berke et al., 2012; Railsback et al., 2018). Other hypotheses call for an onset of the modern El Niño Southern Oscillation (ENSO) regime (e.g., Donders et al., 2008; Conroy et al., 2008; Barron and Anderson, 2010), and/or changes in the sea-surface temperature (SST) gradient between the western and eastern Indian Ocean (the Indian Ocean Dipole, IOD) (Berke et al., 2012; De Boer et al., 2014). If the IOD or ENSO are considered as the main driving mechanisms, an anti-phase relationship between the climate at Rodrigues in the west and that on the eastern margin of the southern Indian Ocean including northern Australia would be expected (see the spatial pattern of El Niño related precipitation anomalies in Supplementary Fig. 1D), which, however, is inconsistent with the phase relationship illustrated in Figure 4. As such, the IOD and ENSO mechanisms do not readily explain the observed climate relationship between Rodrigues and other sites across the southern Indian Ocean.

A close examination of our Rodrigues $\delta^{18}O$ and $\delta^{13}C$ records shows that a persistent multi-centennial drying trend began effectively at ~4.1 ka BP and ended at ~3.5 ka BP, suggesting a prolonged northward shift of the mean position of the ITCZ (Fig. 3 and Supplementary Fig. 1A). This inference, if correct, is partially in contrast with the southward shift of the ITCZ, which is often invoked to explain the weakening of the Asian monsoon since ~4.2 ka BP (e.g., Wang et al., 2005; Kathayat et al., 2017). Thus, the observed drying trends on both the northern and southern fringes of the ITCZ in both hemispheres argue against the model of a southward shift in the mean position of the ITCZ as a viable cause of the 4.2 ka event. A more likely explanation involves an overall contraction in the north-south range of the migrating ITCZ belt in the region (e.g., Yan et al., 2015; Denniston et al., 2016; Scroxton et al., 2017). This mechanism is broadly consistent with the spatial pattern of hydroclimate changes observed in both hemispheres around and after the 4.2 ka event. As mentioned above, the wet period between ~4.1 and 4.0 ka BP recorded at the northern fringe of the ITCZ (Kathayat et al., 2017; 2018) coincided with a wet period on southern limit of the ITCZ as recorded in Dante cave (Railsback et al., 2018), the Zambezi Delta (Schefuβ et al., 2011), Tatos Basin (De Boer et al., 2014), La Vierge cave (this study) and KNI-51 cave (Denniston et al., 2013) (Figs. 4 and 5). The subsequent arid period between ~3.9 and 3.5 ka BP was also basinwide and affected both the northern and southern limits of the ITCZ over the Indian Ocean and adjacent regions (Figs. 4 and 5).

In parallel with drier condition along the southern limit of the austral summer ITCZ, proxy records from Lake Edward (Russell et al., 2003), Lake Victoria (Berke et al., 2012) and Tangga cave (Wurtzel et al., 2018), which are located near the northern limit of the contemporary austral summer ITCZ, also exhibit drier conditions. In contrast, records within the core location of the austral summer ITCZ, such as Lake Challa (Tierney et al., 2011), Lake Tanganyika (Tierney et al., 2008), Lake Malawi (Konecky et al., 2011) and Makassar Strait (Tierney et al., 2012), show either slightly wetter or virtually unchanged hydroclimatic conditions (Figs. 4 and 5). Based on the observed spatial patterns, we suggest that the contraction of the ITCZ both in terms of a north-south meridional shift as well as with respect to its overall width may have played an important role in modulating the hydroclimate in our study area during and after the 4.2 ka event.

6 Author Contributions

H.C., A.S. and H.Y.L designed the research and experiments; H.C., A.S., J.B., Y.F.N. and H.Y.L. completed the fieldwork; H.Y.L., H.C., Y.F.N. and C.S. performed stable isotope measurements and ^{230}Th dating work. A.S., L.Y. and H.Y.L. did the data analyses. H.C., H.Y.L. and A.S. wrote the manuscript, with the help of all co-authors.

7 Competing interests

The authors declare no competing financial interests.

8 Acknowledgments

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9 Data and materials availability

All data needed to evaluate the conclusions in the paper are presented in the paper. Additional data related to this paper may be requested from the authors. The data will be archived at the National Climate Data Center (https://www.ncdc.noaa.gov/dataaccess/paleoclimatology-data). Correspondence and requests for materials should be addressed to H.C. (cheng021@xjtu.edu.cn).

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Figures:

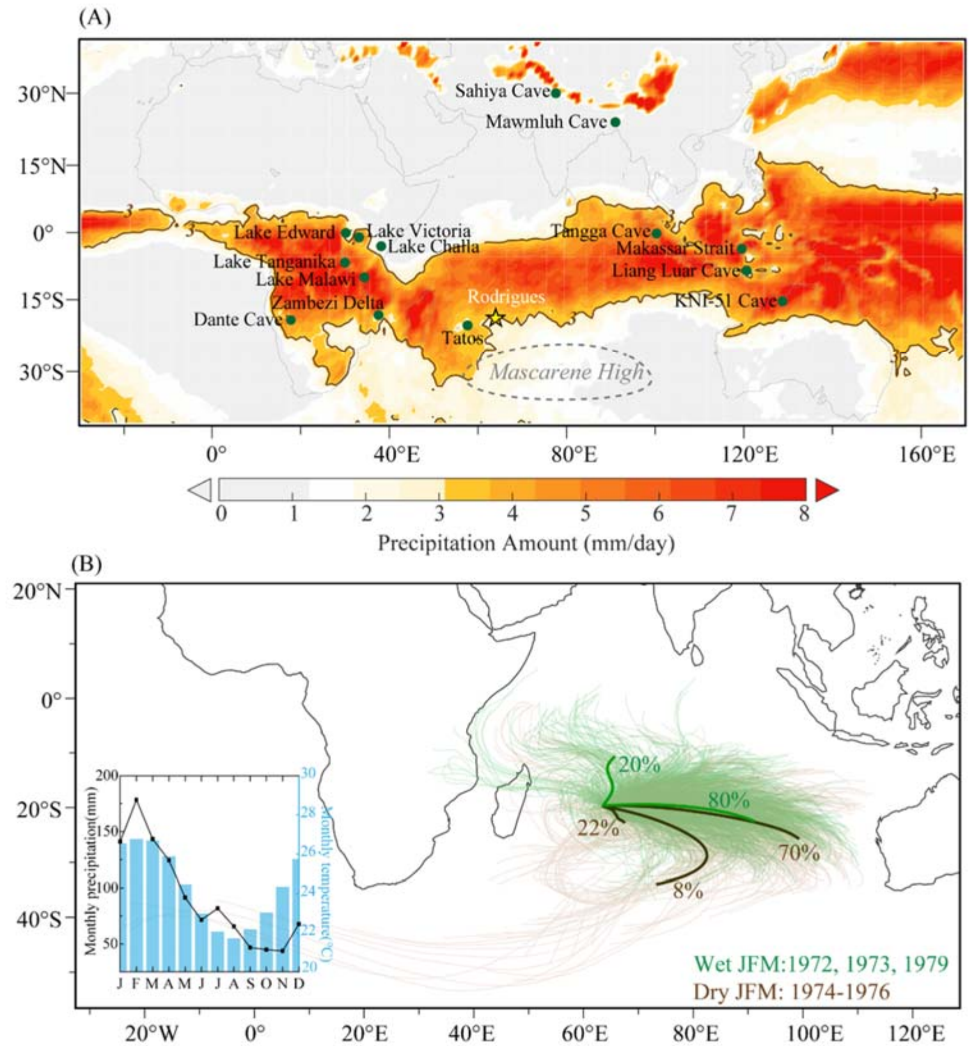


Figure 1. Proxy locations and climatology. (A) Mean January to March (JFM) precipitation from the Tropical Rainfall Measuring Mission (TRMM) (https://trmm.gsfc.nasa.gov/) averaged over the period from 1997 to 2014. Shaded area bounded by solid red lines (3 mm day^{-1} isohyet) depict the mean position of the ITCZ. The dashed line shows the mean position of JFM 850 hPa geopotential height marking the location of the Mascarene High. Locations of Rodrigues Island (yellow star, this study) and other proxy sites (green dots) discussed in the text are also shown. **(B)** 4x daily low-level (~850 hPa) JFM air parcel back (120 hours) trajectory composites for anomalously wet (green) and dry (brown) years. Trajectories were computed using NOAA HYSPLIT model (Draxler and Hess, 1998) using NCEP/NCAR Reanalysis data (Kalnay et al., 1996). Bold lines indicate main cluster tracks associated with trajectories for wetter (green) and drier (brown) years. Inset shows mean monthly rainfall and temperature at Rodrigues averaged over the period 1951 to 2015.

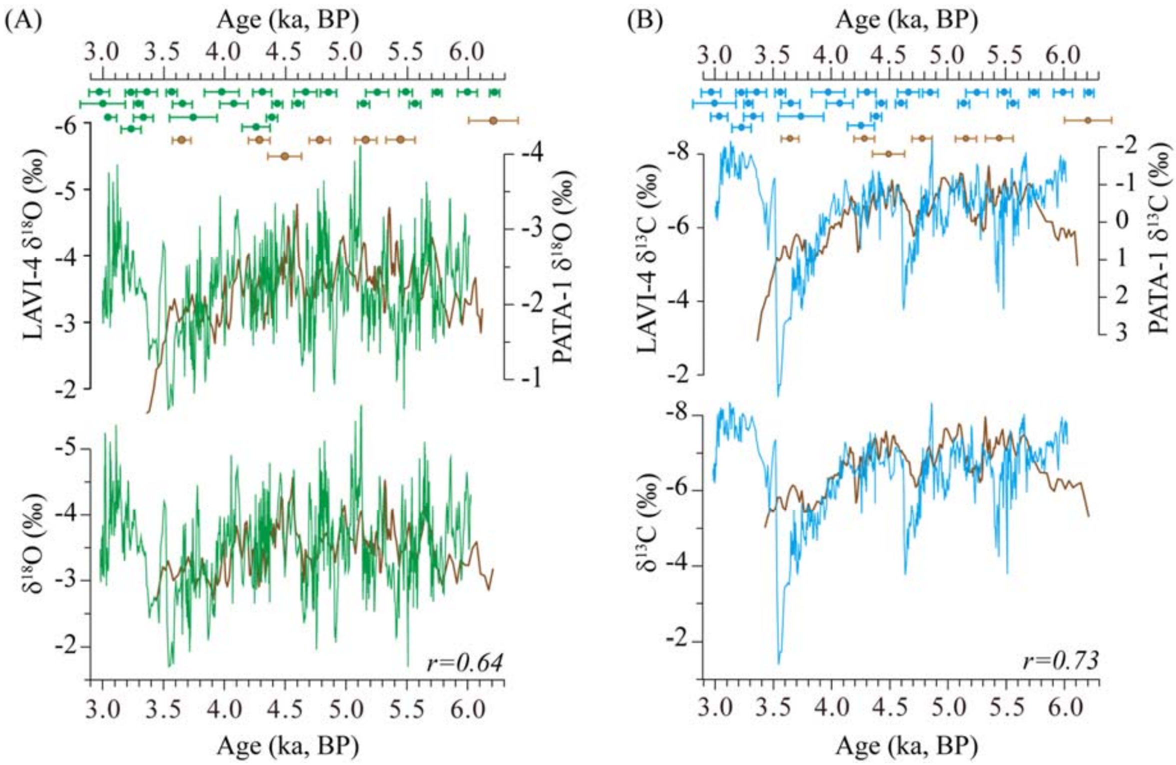


Figure 2. δ¹⁸O and δ¹³C records of LAVI-4 and PATA-1. **(A)** $\delta^{18}O$ profiles of LAVI-4 (green) and PATA-1 (brown) are shown on their independent COPRA age models (top) and ISCAM-derived age models (bottom). The correlation coefficient (*r*) between LAVI-4 and PATA-1 is 0.64. The PATA 1 $\delta^{18}O$ values were adjusted by ~1.3 ‰ to match the LAVI-4 data series. **(B)** Same as in **(A)** but for the $\delta^{13}C$ profiles of LAVI-4 and PATA-1. The PATA-1 $\delta^{13}C$ values were adjusted by ~6.5 ‰ to match the LAVI-4 values.

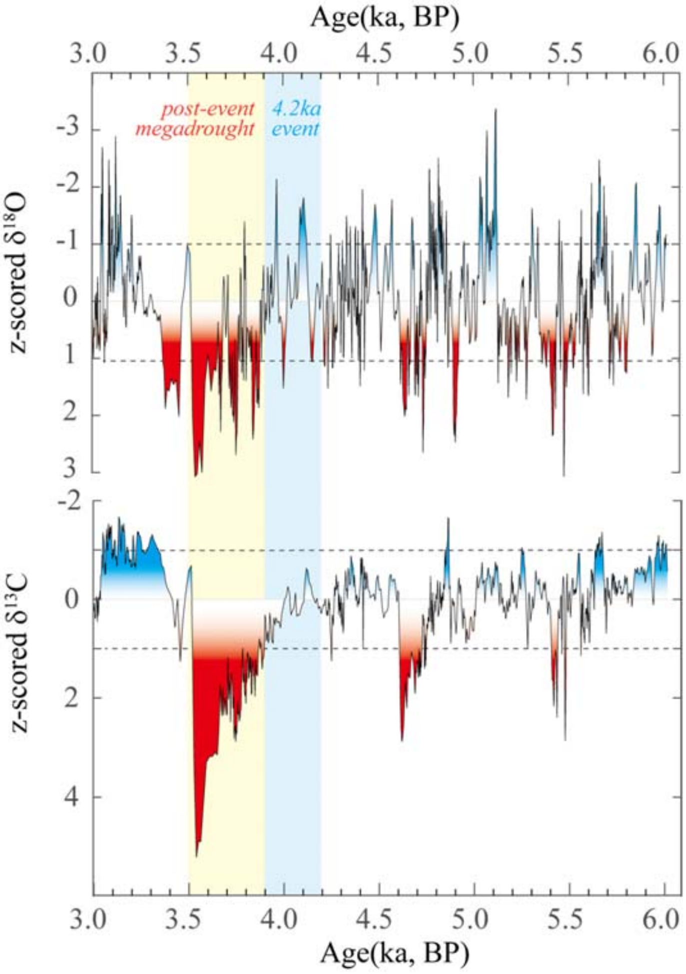


Figure 3. Inferred hydroclimatic variability at Rodrigues from 6 to 3 ka BP. LAVI-4 $\delta^{18}O$ and $\delta^{13}C$ record are z-score transformed. Inferred droughts (z-score > 1) and pluvial episodes (z-score < -1) are shaded (increasing saturation index indicates increasing intensity). Dashed lines indicate 1 standard deviation. The blue bar marks the classical '4.2 ka event' and the yellow bar marks the 'post-event', megadrought, inferred from LAVI-4.

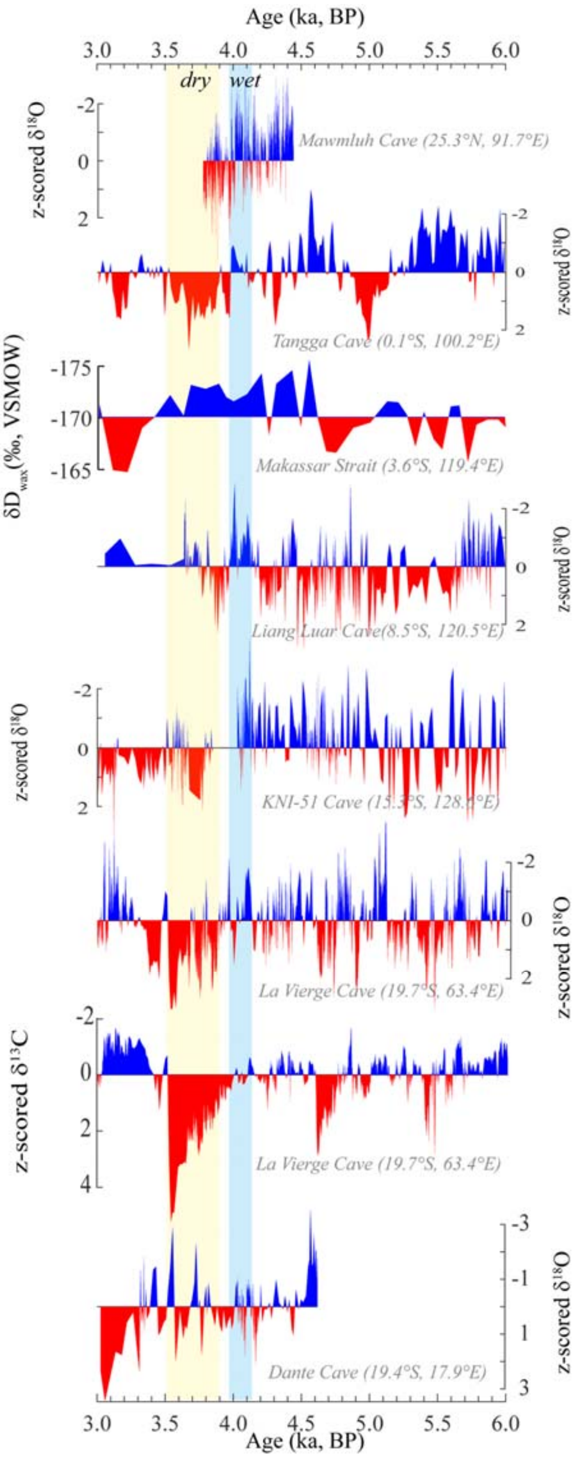


Figure 4. Comparison of LAVI 4 with climate proxy records from the eastern Indian Ocean. From top to bottom, z-score transformed speleothem $\delta^{18}O$ record from Mawmluh cave (Kathayat et al., 2018), Tangga cave, Sumatra, Indonesia (Wurtzel et al., 2018), $\delta D_{leaf\ wax}$ record from marine sediment core BJ8-03-70GGC in the Makassar Strait (Tierney et al., 2012), z-score transformed speleothem $\delta^{18}O$ records from Liang Luar cave, western Flores, Indonesia (Griffiths et al., 2009), KNI-51 cave, Kimberley, northwestern Australia

(Denniston et al., 2013), La Vierge cave, Rodrigues (this study), and Dante cave, northeastern Namibia (Railsback et al., 2018). Shaded vertical bars mark periods of drier and wetter conditions.

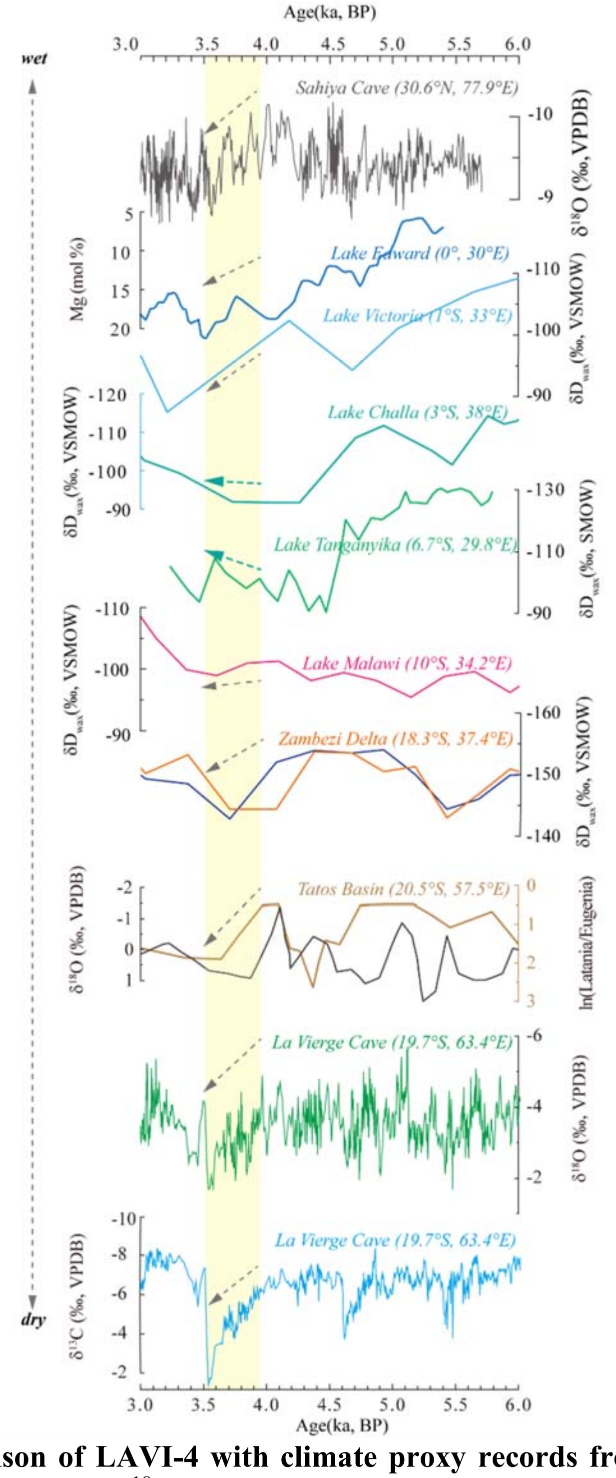
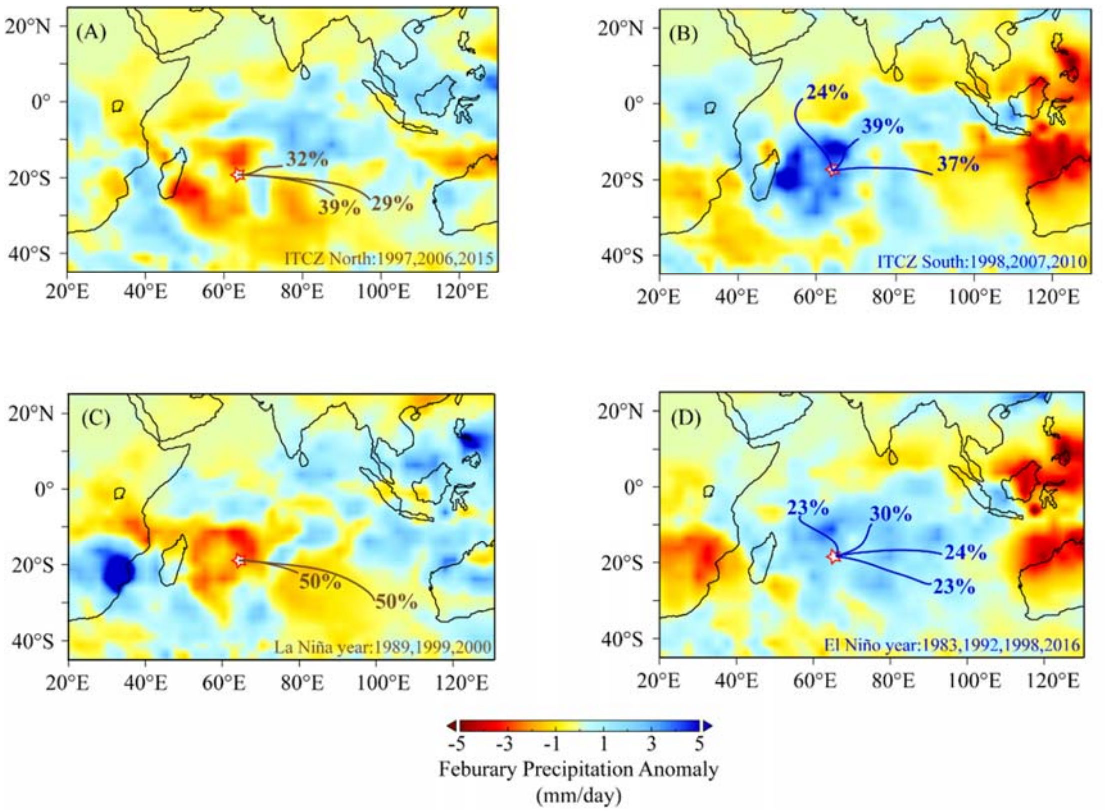


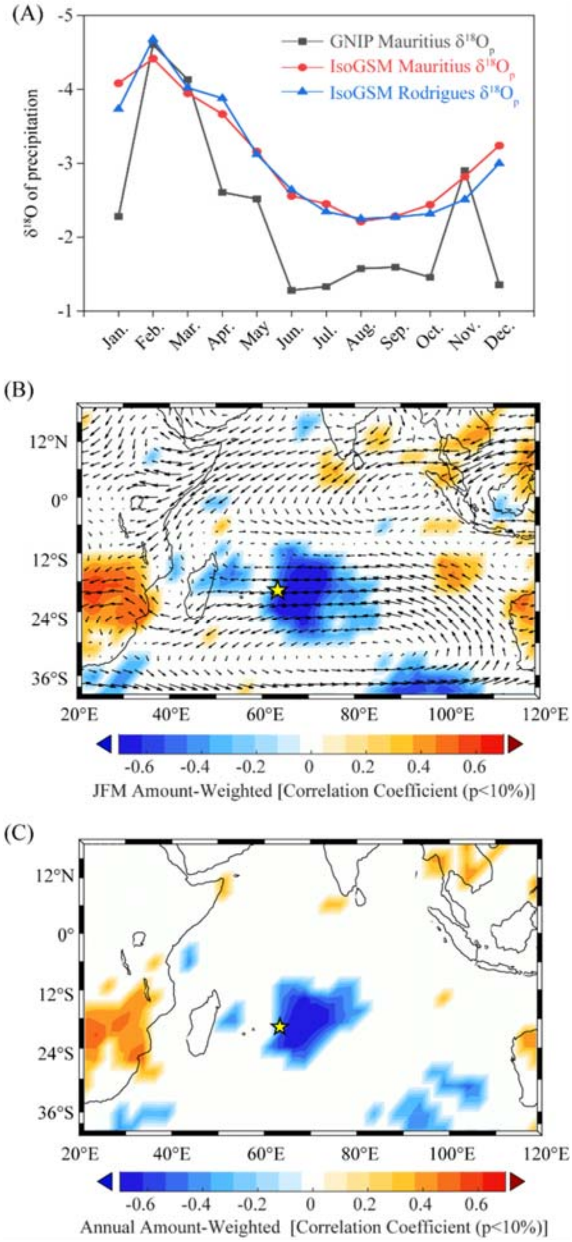
Figure 5. Comparison of LAVI-4 with climate proxy records from India and East Africa. From top to bottom: $\delta^{18}O$ record from Sahiya cave, North India (Kathayat et al., 2017), Mg concentration of endogenic calcite from Lake Edward (Russell et al., 2003),

$\delta D_{leaf\ wax}$ records from Lake Victoria (Berke et al., 2012), Lake Challa (Tierney et al., 2011), Lake Tanganyika (Tierney et al., 2008), Lake Malawi (Konecky et al., 2011), δD of n-C_{29} alkanes (dark blue) and n-C_{31} alkanes (orange) from the Zambezi delta (Schefuβ et al., 2011), $\delta^{18}O$ record (black) and ln (Latania/Eugenia) records (brown) from Tatos basin, Mauritius (De Boer et al., 2014), and the LAVI-4 $\delta^{18}O$ and $\delta^{13}C$ record from La Vierge cave (this study). The shaded vertical bar marks the megadrought from ~ 3.9 to 3.5 ka BP. Grey and green dashed arrows mark the drying and wet trend inferred from East Africa lake records, respectively. All y axes are inverted to show drier conditions down.

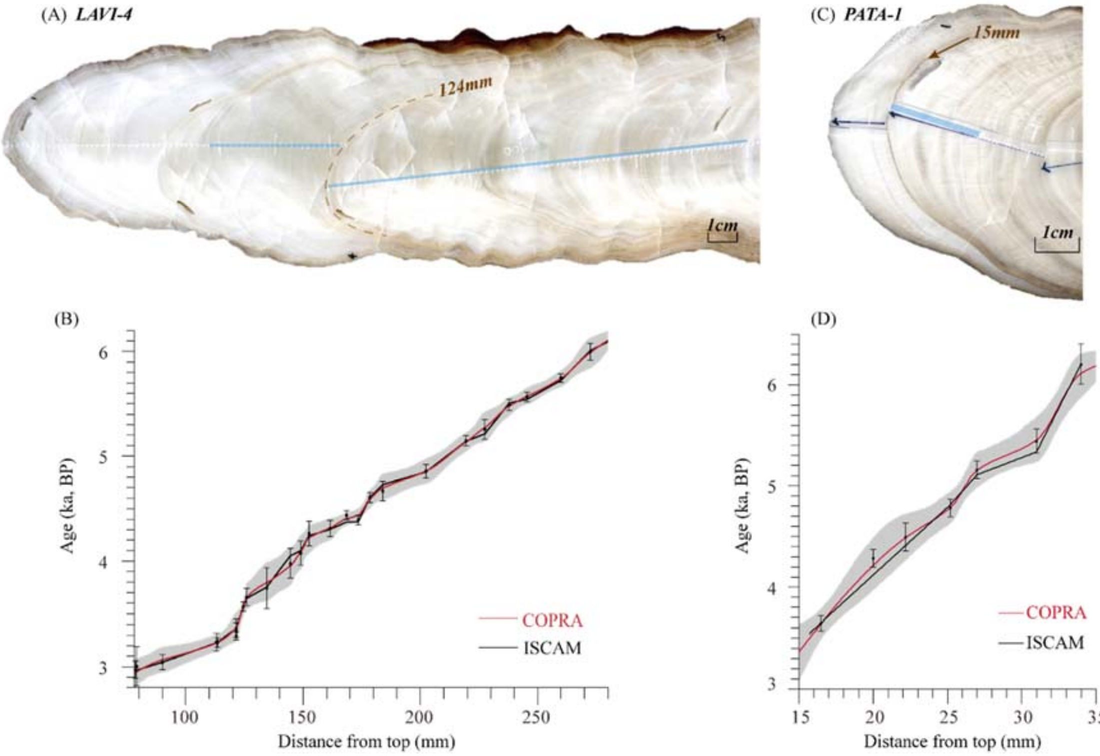
Supplementary figures:



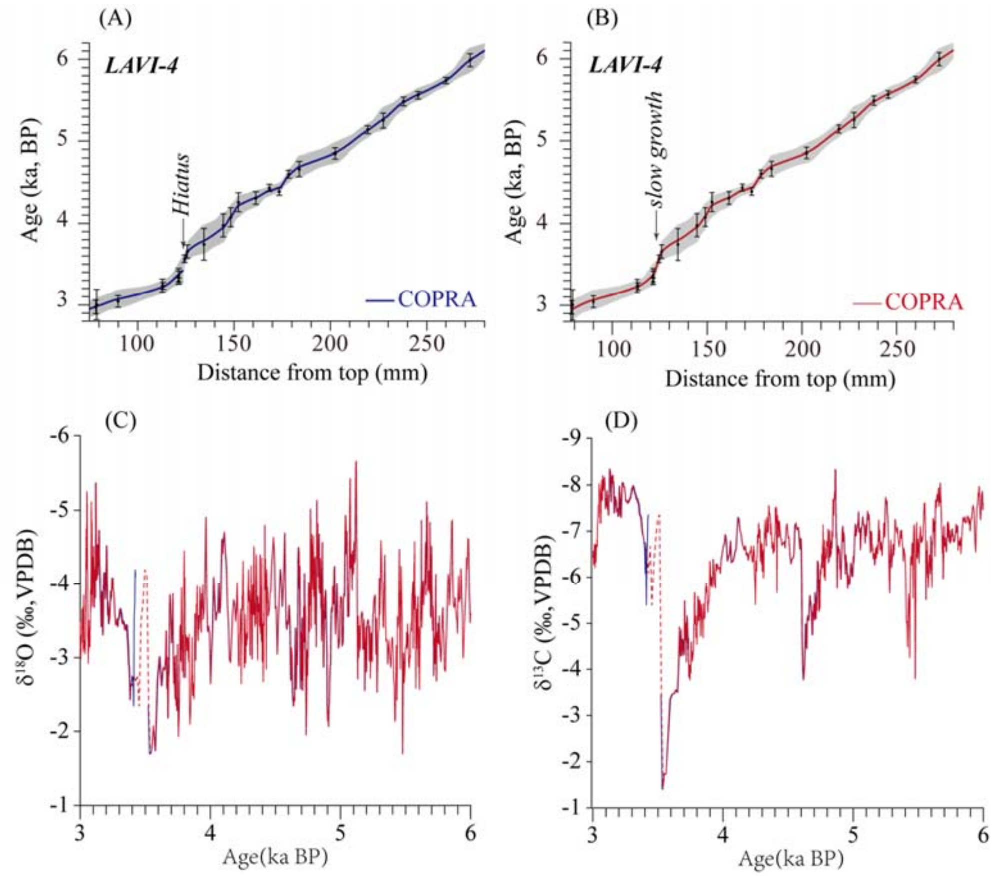
Supplementary Fig. 1. ITCZ and ENSO dynamics. (A and B) Spatial composite maps of precipitation anomalies for February (anomalies calculated with respect to the period 1981-2010) for the years marked by anomalous northward (A, 1997, 2006, 2015) and southward (B, 1998, 2007, 2010) locations of the southern boundary of the ITCZ (Lashkari et al., 2017; Freitas et al., 2017). The maps are overlain by backward (120 hours) low-level air parcel trajectory clusters and their relative contributions. **(C and D)** Same as in **A** and **B** but for La Niña (C, 1989, 1999, 2000) and El Niño (D, 1983, 1992, 1998, 2016) years. Precipitation data from GPCP (Adler et al., 2018).



Supplementary Fig. 2. Modelled and observational data of δ^{18}O in precipitation in the study area. **(A)** Monthly means of simulated $\delta^{18}O_p$ for Mauritius (red) and Rodrigues (blue) from IsoGSM (Yoshimura et al., 2008). Also shown are monthly means of $\delta^{18}O_p$ from six GNIP stations in Mauritius (black) covering the periods 1992-1995 and 2009-2014. **(B and C)** Spatial correlation maps for JFM (**B**) and annual (**C**) amount-weighted IsoGSM $\delta^{18}O_p$ from the nearest grid point to Rodrigues and the GPCP precipitation (GPCP v2.3) (Adler et al., 2018) for the period 1979 to 2016.



Supplementary Fig. 3. Age models of LAVI-4 and PATA-1 stalagmites. (A and C) scan pictures of stalagmite LAVI-4 and PATA-1, respectively. The blue bars line on the stalagmite slabs showing the stable isotope tracks. Dash line in **A** marks the layer at 124 mm. Arrow in **C** marks the layer at 15mm. (**B**) LAVI-4 age models and age uncertainties obtained using COPRA (Breitenbach et al., 2012) (red) and ISCAM (Fohlmeister, 2012) (black). The gray band depicts the 95% confidence interval from COPRA. Error bars on ^{230}Th dates represent 2σ analytical errors. (**D**) Same as in **(B)** but for sample PATA-1.



Supplementary Fig. 4. Comparison of COPRA age model results. (A and B) COPRA age models (Breitenbach et al., 2012) of LAVI-4 with a hiatus at 124 mm **(A)** and no hiatus **(B)**. **(C)** $\delta^{18}O$ time series based on the age models in **A** and **B**. **(D)** $\delta^{13}C$ time series based on the age models in **A** and **B**. The blue and red lines are the age model results from **A** and **B**, respectively. There is a small offset between the two models, except for the period between 3.55 and 3.4 ka BP marked by red dashed lines. The main hydroclimate variations between 6 and 3 ka BP are robust irrespective of the age model used.

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