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

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ABSTRACT

Petrographic features, mineralogy, and stable isotopes from two stalagmites collected from Anjohibe and Anjokipoty Cave allow distinction of three intervals of the Holocene in northwestern Madagascar. The Malagasy early Holocene interval (between ca. 9.8 and 7.8 ka) was wet, and vegetation changes seem to have been controlled by changes in climate. The Malagasy late Holocene interval (after ca. 1.6 ka) also records evidence of wet conditions, but changes in vegetation were influenced by anthropogenic effects, as suggested by the stalagmite $\delta^{13}C$ shift. The Malagasy middle Holocene interval seems to be characterized by drier conditions, relative to the early and late Holocene.

The alternating wet/dry/wet conditions in northwestern Madagascar during each of these Holocene intervals could be linked to the long-term migration of the Inter-Tropical Convergence Zone (ITCZ). Higher southern hemisphere (SH) insolation and globally colder conditions drove the ITCZ's mean position further south, bringing more rainfall to northwestern Madagascar. This condition was favorable for stalagmite deposition. In contrast, higher northern hemisphere (NH) insolation and globally warmer conditions displaced the ITCZ further north, bringing less rainfall to northwestern Madagascar. This condition was not favorable for stalagmite deposition.

The linkage between global cooling and wet conditions in regions of the SH, in response to the southward migration of the ITCZ, is further exemplified at centennial scale by the negative

$\delta^{18}O$ and $\delta^{13}C$ values in northwestern Madagascar during the 8.2 ka cold event when the Atlantic Meridional Overturning Circulation (AMOC) weakened. Weakening of the AMOC 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 brought wet conditions in the SH monsoon regions, such as northwestern Madagascar, and dry conditions in the NH monsoon regions, including the Asian Monsoon and the East Asian Summer Monsoon. This climatic relationship is useful to test for climate models that are used to predict changes in future climate.

1. Introduction

Although much is known about the Holocene climate change worldwide (Mayewski et al., 2004; Wanner and Ritz, 2011; Wanner et al., 2011; 2015), high-resolution climate data for the Holocene period is still regionally limited in the Southern Hemisphere (e.g. Wanner et al. 2008; Marcott et al. 2013; Wanner et al., 2015). This uneven distribution of data hinders our understanding of the spatio-temporal characteristics of Holocene climate change, including our understanding of the most important climate forcings of the Holocene. Some of these forcings would, for example, have an influence on the ITCZ behavior and the monsoonal response in low- to mid-latitude regions (e.g. Wanner et al., 2015; Talento and Barreiro, 2016). Madagascar is particularly a strategic location where such records are needed because it holds a key position in the Indian Ocean (Fig. 1a), and it is seasonally visited by the ITCZ (Inter-Tropical Convergence Zone) with a karst region crossing latitudinal belts (Fig. 1c). Thus, records from Madagascar could complete gaps in paleoclimate reconstruction in the Southern Hemisphere (SH). Records from Madagascar could also help refine paleoclimate simulations that could provide better understanding of the global circulation and the land-atmosphere-ocean interaction during the Holocene.

To fill the knowledge gap about the Holocene climate change in the SH and particularly in Madagascar, and to better understand the paleohydrology in NW Madagascar during the Holocene, we present multiproxy records (stable isotopes, petrography, mineralogy, variability of layer-specific width) from stalagmites from two caves, Anjohibe and Anjokipoty Caves, in northwestern Madagascar. Stalagmites are used because of their potential in storing significant climatic information (e.g. Fairchild and Baker, 2012, p. 9–10), and in Anjohibe cave, recent studies have shown the replicability of paleoclimate records from stalagmites (e.g. Burns et al., 2016). The two stalagmites investigated here provide replication of paleoclimate records, which allow us to characterize the Holocene climate change in northwestern Madagascar. First we infer the climatic significance from direct interpretation of the stalagmite records. With a better understanding of Madagascar's paleoclimate, we will then investigate on the possible climatic drivers of tropical climate changes to draw a more comprehensive conclusion on the major factors controlling its hydrological cycle.

2. Setting

2.1. Regional environmental setting

Two stalagmites, ANJB-2 and MAJ-5, were collected from Anjohibe and Anjokipoty caves, respectively, in the region of Majunga of northwestern Madagascar (Fig. 1). Anjohibe (S15° 32' 33.3"; E046° 53' 07.4") and Anjokipoty (S15° 34' 42.2"; E046° 44' 03.7") are separated by about 16.5 km (Fig. 1c). Their location in the zone visited by the ITCZ (e.g. Nassor and Jury, 1998) makes them a good place 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's climate in general belongs to the tropical savanna climate (Aw) of Köppen-Geiger climate classification, with 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).

Anjohibe and Anjokipoty 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). Replicability of stable isotope records from Anjohibe Cave stalagmites (e.g. Burns et al., 2016) further suggests the potential of stalagmites to provide robust paleoclimate information for Madagascar.

2.2. The Holocene in northwestern Madagascar

Little is known about Holocene climate change in northwestern Madagascar, and little is also known about the major drivers of long-term climatic changes there. Most paleoclimate information from northwestern Madagascar covers the last two millennia with more focus on the anthropogenic effects on the Malagasy ecosystems (e.g. Crowley and Samonds, 2013; Burns et al., 2016). This is because several studies revealed coincidence of Madagascar's megafaunal extinction with human arrival around 2-3 ka BP (e.g. see Table 1 of Virah-Sawmy et al., 2010; MacPhee and Burney, 1991; Burney et al., 1997c; Crowley, 2010). Long-term records are very scarce. The only records that cover longer time interval were 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). Both sediments provided useful information about the paleoenvironmental changes in northwestern Madagascar, but linkages to global climatic changes were not fully understood. Madagascar is however a key location in the SH that could provide meaningful paleoclimate information about the global circulation during the Holocene.

3. Methods

Stalagmites ANJB-2 and MAJ-5 were radiometrically dated using the multi-collector ICP-MS of the University of Minnesota, USA and of the Stable Isotopes Laboratory of Xi'an, in Jiaotong, China. Twenty-two powdered samples of approximately 50 to 200 mg were extracted from Stalagmite ANJB-2 and nine samples from Stalagmite MAJ-5 (Tables S1 and S2). The stalagmites' chronology was constructed using the StalAge1.0 algorithm of Scholz and Hoffman (2011) and Scholz et al. (2012). The StalAge scripts were run on the statistics program R version 3.2.2 (2015-08-14). The age models were adjusted in respect to identified hiatal surfaces, implementing the approach of Railsback et al. (2013; see their Fig. 9).

Petrography and mineralogy of the two stalagmites were investigated using hand samples' polished surfaces and a scanned image of it (measuring the layer-specific width), microscopic observation of eleven oversized thin sections (3 x2 in), and X-ray diffraction of powdered spelean layers with CoKα radiation at a 2θ angle between 20° and 60° using a Bruker D8 X-ray Diffractometer of the Department of Geology of the University of Georgia.

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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 was done by replicating every tenth sample of Stalagmite MAJ-5 on the MAT 253 mass spectrometer. The replicates suggest strong correlation (Fig. S4). 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. These transformations were done here to compensate for the aragonite's inherent fractionation of heavier isotopes as have been done in previous studies (e.g. Sletten et al., 2013; Voarintsoa et al., 2016, in revision). With these transformations, the corrected isotopic values remove the mineralogical bias in isotopic interpretation between calcite and aragonite.

4. Results

4.1. Radiometric data

Results from radiometric analyses of the two stalagmites are presented in Table S1 and Table S2. Stalagmite ANJB-2 has a ^{234}U range from 64±0 to 9833±44 ppb and a ^{232}Th range from 180±8 to 39850±809 ppt. Corrected ^{230}Th suggests that it was deposited between ca. 8977±50 and 161±64 yr. BP. Stalagmite MAJ-5 has a ^{234}U range from 1224±4 to 12609±83 ppb and a ^{232}Th range from 3044±63 to 38990±842 ppt. Corrected ^{230}Th suggests that is was deposited between ca. 9796±64 and 150±24 yr. BP. Those age ranges most completely span the Holocene interval in northwestern Madagascar. StalAge model and petrography highlight three distinct intervals of the Holocene (Fig. 2): (1) between ca. 9.8 and 7.8 ka BP, with evidence of $CaCO_3$ deposition, (2) between ca. 7.8 and 1.6 ka BP, with a noticeable long-term hiatus, and (3) after ca. 1.6 ka BP when the stalagmites resumed to grow. These intervals will be called Malagasy early Holocene interval

(MEHI), Malagasy mid-Holocene interval (MMHI), and Malagasy late Holocene interval (MLHI) respectively.

4.2. Stable isotopes

Raw values of $\delta^{18}O$ and $\delta^{13}C$ for Stalagmite ANJB-2 range from –8.85 to –2.27‰, and from –11.00 to +5.15‰, respectively, relative to VPDB. The mean values are –4.97‰ and –4.18‰ respectively for $\delta^{18}O$ and $\delta^{13}C$. Raw values of $\delta^{18}O$ and $\delta^{13}C$ in Stalagmite MAJ-5 range from –8.80 to –0.85‰, and from –9.44 to +2.60‰, respectively, relative to VPDB. The mean values are – 4.85‰ and –4.38‰ respectively for $\delta^{18}O$ and $\delta^{13}C$, but distinguishable between MEHI and the MLHI (Fig. 3). In both stalagmites, the amplitude of $\delta^{18}O$ fluctuations stayed constant throughout the Holocene; whereas the $\delta^{13}C$ profile shows a dramatic shift toward greater values (i.e. from - 10.90‰ to +3.75‰, VPDB) at ca. 1.5 ka BP. Values of $\delta^{13}C$ only parallel those of $\delta^{18}O$ during the MEHI (Fig. 3).

The MEHI and the MLHI are isotopically distinct (Fig. 3a). The MEHI is characterized by statistically correlated $\delta^{18}O$ and $\delta^{13}C$ (r^2=0.65 and 0.53), and much depleted $\delta^{13}C$ values (ca. –11.0 to –4.0 ‰). The 8.2 ka event, a widespread event in the NH (e.g. Alley et al., 1997), is also identified in the stalagmite records. Stalagmite $\delta^{18}O$ and $\delta^{13}C$ values both decreased to a minimum of –6.78 and –10.88‰, respectively at that interval (Figs. 3 and 7). In contrast to the MEHI, the MLHI's $\delta^{18}O$ and $\delta^{13}C$ are poorly correlated (r^2=0.25 and 0.17), and $\delta^{13}C$ values are more enriched (Fig. 3).

4.3. Mineralogy, petrography, and layer-specific width

In both stalagmites, the hiatus of deposition (see Sect. 4.1) is characterized by a well-developed Type L surface (Figs. 2b, 6S). Petrography and mineralogy are distinct before and after that hiatus (Fig. 2). Below the hiatus, laminations are well preserved in both stalagmites. Above the hiatus, laminations are not well-preserved, although noted at some intervals.

In Stalagmite ANJB-2, the layer-specific width varies from 37 to 26.5 mm with a mean of 30 mm. It narrows to 28 mm at the hiatus (Fig. 2b). Below the hiatus, mineralogy is dominated by aragonite, although a few thick layers of calcite are also identified. A thin (~2-3 mm) but remarkable layer of white, very soft, and porous aragonite is identified just below the hiatus (Fig.

S6). This layer is capped with a very thin layer of dirty material. Above the hiatus, mineralogy is also composed of calcite and aragonite, with dominance of calcite, and the calcite layers contain some macro-cavities that are mostly off-axis macroholes (Shtober-Zisu et al., 2012).

In Stalagmite MAJ-5, the layer specific width varies from 50 to 22 mm with a mean of 35.5 mm. It narrows to 22 mm at the hiatus (Fig. 2b). Below the hiatus, mineralogy is a mixture of calcite and aragonite. Above the hiatus, mineralogy is mainly calcite and macro-cavities are also distributed throughout that upper part of the stalagmite.

4.4. Summary of the results

The records from Stalagmites ANJB-2 and MAJ-5 suggest three distinct intervals of the Holocene. The MEHI (between ca. 9.8 and 7.8 ka BP), with evidence of stalagmite deposition, is characterized by statistically correlated $\delta^{18}O$ and $\delta^{13}C$ (r^2=0.65 and 0.53) and more negative $\delta^{13}C$ values (ca. –11.0 to –4.0 ‰). The MMHI (between ca. 7.8 to 1.6 ka BP) is marked by a long-term hiatus of deposition, which is preceded by a well-developed Type L surface in both Stalagmite ANJB-2 and MAJ-5 (Fig. 2; Fig. S6). The Type L surface is observed as an upward narrowing of the stalagmite's width and layer thickness. It is particularly well-developed in Stalagmite MAJ-5 (Fig. S6). In the other Stalagmite ANJB-2, the hiatus at the Type L surface is preceded by approximately 3 mm-thick layer of highly porous, very soft, and fibrous white crystals of aragonite (the only aragonite with such properties), and it is topped by a thin and well-defined layer of detrital materials (Fig. S6), further supporting the presence of a hiatus. Finally, the MLHI (after ca. 1.6 ka BP) is characterized by poorly correlated $\delta^{18}O$ and $\delta^{13}C$ (r^2=0.25–0.17). This interval is additionally marked by a shift in $\delta^{13}C$ and greater $\delta^{13}C$ (Fig. 3).

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5. Discussion

5.1. Paleoclimate significance of stalagmite growth and non-growth: implications for paleohydrology

Stalagmites are secondary cave deposits, which are $CaCO_3$ precipitates from cave dripwater. Calcium carbonate precipitation occurs by CO_2 degassing, which increases the pH of the dripwater and thus increases the concentration of CO_3^{2-}. In some cases, evaporation, which increases the Ca^{2+} and/or CO_3^{2-} of the dripwater, may also be important. Degassing occurs because the high-PCO_2 water from the epikarst meets the low-PCO_2 cave air, while evaporation occurs when humidity inside the cave is relatively low. The fundamental equation for stalagmite deposition is shown in Eq. 1.

$$Ca^{2+}_{(aq)} + 2HCO^{-}_{3\,(aq)} \rightleftharpoons CaCO_{3\,(s)} + CO_{2\,(g)} + H_2O_{(l)} \text{ (Eq. 1)}$$

Growth and non-growth of stalagmites depends on several factors that could be mainly linked to water availability, which in turn is linked to climate (more water during warm/rainy seasons and less water during cold/dry seasons). Water is the main dissolution and transport agent for most chemicals in speleothems. Cave hydrology varies significantly over time in response to climate, and this variability influences the formation or dissolution of $CaCO_3$. In this regard, calcium carbonate does not form if the water feeding the cave is very little to absent, or if it is too much. Absence of groundwater recharge most typically occurs during extremely dry conditions, whereas excessive water input to the cave occurs during extremely wet conditions. In the latter scenario, water is undersaturated and flow rates are too fast to allow degassing. Oftentimes, water availability could be reflected in the extent of vegetation above and around the cave, as this requires enough moisture from the soil or from the shallow groundwater. Surface biomass supplies most of the CO_2 to the soil epikarst, and this could contribute to the stalagmites' processes of formation. Growth and non-growth of stalagmites could be associated with cave dripwater fed by atmospheric precipitation, and this could be linked to climatic conditions at the time when stalagmites grew.

Major hiatuses in stalagmite deposition could be marked by variety of features, including the presence of erosional surfaces, chalkification, dirt bands/detrital layers, deviation of growth axis, and/or sometimes by color changes (e.g. Holmgren et al., 1995; Dutton et al., 2009; Railsback et al., 2013; Railsback et al., 2015; Voarintsoa et al., 2016; this study). Railsback et al. (2013) were specifically able to identify significant features in stalagmites that allow distinction between non-deposition during extremely wet (Type E) and non-deposition during extremely dry conditions (Type L; Fig. 2b). Physical properties of stalagmites that support these extreme dry and wet events are summarized in Table 1 of Railsback et al. (2013) and the mechanism is explained in their figure 5.

Type E surfaces are layer-bounding surfaces between two spelean layers when the underlying layers show evidence of truncation. The truncation results from dissolution or erosion (thus the name "E") of the previously-formed layers of stalagmites by abundant undersaturated water. Type E surfaces are commonly capped with a layer of calcite (Railsback et al., 2013). This mineralogical trend is not surprising in stalagmites as calcite commonly forms under wetter conditions (e.g. Murray, 1954; Pobeguin, 1965; Siegel, 1965; Thrailkill, 1971; Cabrol and Coudray, 1982; Railsback et al. 1994; Frisia et al., 2002). Additionally, non-carbonate detrital materials are commonly abundant with varying grain size (i.e. from silt- to sand-size; Railsback et al., 2013).

Type L surfaces, on the other hand, are layer-bounding surfaces where the layers became narrower upward and thinner toward the flank of the stalagmite. The decrease in thickness and width of the stalagmites upward is an indication of lessening in deposition (thus the name "L"; Railsback et al., 2013). Aragonite is a very common mineralogy below the surface, especially in warmer settings. Layers of aragonite commonly form under drier conditions (Murray, 1954; Pobeguin, 1965; Siegel, 1965; Thrailkill, 1971; Cabrol and Coudray, 1982; Railsback et al. 1994; Frisia et al., 2002). Non-carbonate detrital materials are scarce, and if they are present, they tend to form a very thin horizon of very fine dust material (Railsback et al., 2013), typical characteristics for a hiatus in deposition. Identification of Type L surfaces has been aided by measuring the layer-specific width, or LSW (e.g. Sletten et al., 2013; Railsback et al., 2014), an approach that is also performed in this study.

5.2. Holocene climate reconstruction in northwestern Madagascar

Although the specific boundaries between the early, mid, and late Holocene have been proposed for global application (Walker et al., 2012; Head and Gibbard, 2015), their use is still

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spatially limited (e.g. Wanner et al., 2015). The age models and the petrographic features of Stalagmites ANJB-2 and MAJ-5 suggest three distinct but different intervals (MEHI, MMHI, and MLHI) that could be used to characterize the Holocene in northwestern Madagascar, as proposed in Section 4.1. These intervals are modeled in the three simplified sketches of Figure 4. In this paper, these Malagasy intervals were provided here not to argue against the previously proposed intervals of the Holocene (Walker et al., 2012; Head and Gibbard, 2015). Instead, they were adopted here to ease discussion of the available records. For comparison, those intervals are shown in Fig. 4d.

5.2.1. Malagasy **early Holocene interval (between ca. 9.8 to ca. 7.8 ka BP)**

Stalagmite deposition during the early Holocene suggests that Anjohibe and Anjokipoty caves were sufficiently supplied with water to allow $CaCO_3$ precipitation, in accord with Eq.1. This in turn implies relatively wet conditions that could reflect longer summer rainy seasons, or wet years in northwestern Madagascar (see Supplementary Text 1 and Fig. S9). The correlative $\delta^{13}C$ and $\delta^{18}O$ values further suggest that vegetation consistently responded to changes in moisture availability, which in turn is dependent on climate.

One striking aspect we found in Stalagmite ANJB-2 is the local minima in $\delta^{18}O$ (~ –6.78‰) and $\delta^{13}C$ (~ –11.00‰) centered at 8.2 ka BP (Figs 3 and 7). X-ray diffraction data for this period, at 195–202 mm from the top of the stalagmite, suggest that the mineralogy at that age is calcite (Fig. S8). The decrease in stable isotopes of oxygen and carbon and the presence of calcite mineralogy at the same interval combine to suggest a wet 8.2 ka event in northwestern Madagascar. The 8.2 ka event is a prominent cold event in the northern Atlantic records and many NH terrestrial records. It may have been triggered by a release of freshwater from the melting Laurentide ice sheet into the North Atlantic basin (e.g. Alley et al., 1997; Barber et al., 1999). Freshwater influx to the Atlantic could have altered the Atlantic Meridional Overturning Circulation, and could eventually influence the climate of Madagascar (Sect. 5.3.3). The $\delta^{18}O$ and $\delta^{13}C$ records from Stalagmite ANJB-2 show similar features as the $\delta^{18}O$ of the Greenland ice core records (GRIP and NGRIP, Fig. 7), and suggest that the cold 8.2 ka event in the Northern Hemisphere records coincide with wet period in northwestern Madagascar. This is the first time in our records that reveals a strong link between paleoenvironmental changes in Madagascar and abrupt climatic events in the Northern Hemisphere records, suggesting that Madagascar climate was also very sensitive to such abrupt climate events.

5.2.2. Malagasy mid-Holocene interval (ca. 7.8 to 1.6 ka BP)

The mid-Holocene hiatus in both stalagmites could be interpreted in two ways: an interval of extremely wet conditions or an interval of extremely dry conditions. In the scenario of extremely wet conditions, the dripwater rate must have been very high to allow degassing, thus inhibiting $CaCO_3$ precipitation. The excesses of water infiltrating into the cave could have dissolved previously deposited stalagmite layers. However, the absence of a major Type E surface (erosional surface; Railsback et al., 2013) at the hiatus suggests that extreme wet conditions did not prevail during the mid-Holocene.

In the case of extremely dry conditions, the cave must have not received sufficient dripwater to allow the stalagmites to grow. Several lines of evidence in both stalagmites suggest a dry mid-Holocene in northwestern Madagascar. First, the major Type L surfaces identified in Stalagmite MAJ-5 and ANJB-2 at ca. 62 and 117 mm respectively from the top of each stalagmite suggest that the mid-Holocene was drier. In Stalagmite ANJB-2, this Type L surface is preceded by a thin (ca. 3 mm) layer of aragonite, a $CaCO_3$ polymorph frequently found in stalagmites to indicate intervals of drier conditions (Murray, 1954; Pobeguin, 1965; Siegel, 1965; Thrailkill, 1971; Cabrol and Coudray, 1982; Railsback et al. 1994; Frisia et al., 2002). This Type L is also capped with a very thin layer of dust materials, similar to the layer described in Railsback et al. (2013). This inference of drier mid-Holocene interval is additionally supported by a decrease in the layer-specific width of the stalagmites towards the hiatus (Fig. 2B), quantifying the decrease in $CaCO_3$ deposition, which could have started at the end of the early Holocene and continued to the mid-Holocene.

Although records are missing during the mid-Holocene in both of our stalagmites, the absence of stalagmite deposition at a major Type L surface (Fig. 2), which is preceded by a thin porous layer of aragonite, would very likely suggest that the cave was not sufficiently supplied with water, and thus climate was drier then compared to the early Holocene, hence we name is "Malagasy mid-Holocene dry period". The dry mid-Holocene was also felt in other regions of

Madagascar (e.g. Gasse and Van Campo, 1998; Virah-Sawmy et al., 2009). Drier intervals in northwestern Madagascar would imply drier summer seasons with less rainfall (reflecting a short visit of the ITCZ), rather than simply dry climate with no rainfall at all (see Supplementary Text 1 and Fig. S9). It is therefore possible to expect that at some locations in the cave, some stalagmites could still grow but very slowly, such as ANJ94-5 (Wang and Brook, 2013, Wang, 2016).

5.2.3. Malagasy late Holocene interval (ca. 1.6 ka to present)

The resumption of stalagmite deposition after ca. 1.6 ka BP suggests that climate in northwestern Madagascar returned to relatively wet conditions, at least similar to the early Holocene climate conditions. Stable isotopes of carbon ($\delta^{13}C$) profile display a shift from depleted to enriched values at ca. 1.5 ka BP (Fig. 3; Fig. S7), as have been observed in previous stable isotope profiles in Anjohibe (e.g. Burns et al., 2016; Voarintsoa et al., in revision), suggesting that the late Holocene's vegetation was different from that of the early Holocene. This shift has been linked to a change from a C_3-dominated landscape to a C_4-dominated landscape, the cause of which has been linked to recent human activities (e.g. Crowley and Samonds, 2013; Burns et al., 2016; Crowther et al., 2016). The decrease in $\delta^{13}C$ in Stalagmite MAJ-5 after 0.8 ka BP (Fig. 3), compared to the high $\delta^{13}C$ of Stalagmite ANJB-2, is open to further investigation as to whether linked to local vegetation highly disturbed by human activities, cave micro-climate, or some other problems encountered during chemical analyses.

Although the last ca. 1.6 ka BP interval records overall wetter conditions, it was also interrupted by some occasional dryness, as suggested by several positive peaks in the Stalagmite $\delta^{18}O$ records. Drier intervals during the late Holocene were, for example, revealed in Anjohibe between ca. AD 755 and 795 (i.e. 1195–1155 yr. BP; Voarintsoa et al.'s, in revision), and in previous paleoenvironmental studies, in which a peak drought around 1300–950 Cal BP was reported (Burney, 1987a, b; Burney, 1993; Matsumoto and Burney, 1994; Virah-Sawmy et al., 2009).

5.3. Holocene climate in northwestern Madagascar: implications for the ITCZ dynamics

The periods of deposition of the two stalagmites ANJB-2 and MAJ-5 from Anjohibe and Anjokipoty Caves respectively during the MEHI and the MLHI suggests that these intervals were relatively wetter than the MMHI. The absence of an increasing trend in the $\delta^{18}O$ values, with a consistent amplitude of fluctuations, throughout the Holocene suggest that northwestern Madagascar has been consistently visited by the ITCZ. However, the alternating wet/dry/wet intervals during the early, mid, and late Holocene suggest that, in addition to the seasonal migration of the ITCZ, these long-term climate changes could be associated with the duration of the ITCZ visit in the Southern Hemisphere, leading to wet or dry years in Madagascar (also see Supplementary Text 1 and Fig. S9).

The length of visit of the ITCZ in northern or southern hemisphere has been linked to the latitudinal shift or latitudinal migration of the ITCZ. When the ITCZ's mean position is south (often mentioned in several papers as southward migration of the ITCZ), many regions in the southern Hemisphere become wetter because summer rainy seasons get longer (e.g. Voarintsoa et al., 2016), and monsoonal rainfall during summer seasons could have intensified. When the ITCZ's mean position is north (i.e. referred usually as a northward migration of the ITCZ), many regions in the southern hemisphere become drier as summer rainy seasons become shorter, when monsoonal rainfall during summer seasons weakened.

In northwestern Madagascar, stalagmite deposition during the MEHI and the MLHI could suggest sufficient dripwater supply that could reflect wetter conditions, linked to southward mean position of the ITCZ. The hiatus in deposition during the MMHI could suggest a northward migration of the ITCZ. Factors that could influence the mean position of the ITCZ include change in insolation, difference in temperature between the two hemispheres, glaciers advances that indicate global cold conditions, and the alteration of the thermohaline circulation. These factors are discussed in detail further below.

5.3.1. ITCZ and insolation

The ITCZ migrates southward in austral summer and northward in boreal summer in response to seasonal insolation. This migration has also been observed at decadal, centennial, and millennial scale (e.g. Haug et al., 2001; Voarintsoa et al., 2016). If we assume that insolation is the sole driver of the ITCZ's latitudinal migration, comparison of the insolation curves of Berger and Loutre (1991) and the stable isotope profiles and the timing of deposition of stalagmites ANJB-2 and MAJ-5 (Fig. 5a) suggests that high winter insolation in the southern hemisphere could have been responsible of the southward migration of the ITCZ during the early Holocene. This could have increased the number of summer months in northwestern Madagascar, without necessarily intensifying the monsoon strength. On the other hand, the southward migration of the ITCZ during the late Holocene could be linked to high summer insolation (Fig. 5). In such conditions, it could be possible that monsoonal rainfall in northwestern Madagascar intensified (see Supplementary Text 1 and Fig. S9).

Recognizing that application of the insolation curve of Berger and Loutre (1991) to paleohydrology in northwestern Madagascar might seem subjective, we also compared our records with the solar radiation reconstruction from ^{14}C residual records of Stuiver et al. (1998). The stalagmite $\delta^{18}O$ records relate well to the reconstructed solar irradiance fluctuations during the early Holocene. Negative $\delta^{18}O$ values, indicative of wetter conditions in northwestern Madagascar, correspond to high $\Delta^{14}C$ residuals values, indicative of low solar irradiance (Fig. 5). A similar but opposite relationship has been observed during the Holocene Asian Monsoon in Dongge Cave, southern China, a region visited by the ITCZ during boreal summers (Wang et al., 2005). Figure 2 of Wang et al. (2005) suggests that higher solar irradiance (smaller $\Delta^{14}C$) corresponds to a stronger Asian Monsoon. This antiphase relationship between northwestern Madagascar and southern China's monsoonal response, for example, could suggest that the distribution of energy related to solar irradiance leads to shifts of the ITCZ, and this is felt in both hemispheres.

Comparing the stalagmite $\delta^{18}O$ records with the same ^{14}C residual records of Stuiver et al. (1998), the late Holocene paleohydrology linkage to insolation is not as obvious as the early Holocene. This could be explained by the complexity of the climate drivers during the late Holocene. Studies report that the late Holocene climate has changed in response to several overlapping effects of the orbitally driven insolation, volcanic eruptions, changes in solar irradiance (e.g. Wanner et al., 2008), and changes in regional to global-scale variations in temperature (e.g. Neukom et al., 2014; Chambers, 2015).

For the mid-Holocene, our inference of a drier Madagascar paleoclimate seems to agree with the paleoclimate simulation of Braconnot et al. (2007), suggesting that the northern

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hemisphere insolation increased. This insolation hypothesis was briefly reviewed in Chiang (2009; see his Fig. 6). Per Chiang's review, the predominant climate forcing of the mid-Holocene (centered at ~6 ka) was a pronounced change to the insolation, which was primarily due to precessional changes in Earth's orbit. He added that the Earth was nearer to the Sun in boreal summer than boreal winter, and NH summers were more intense than today. Quantification of the mean ITCZ position using a set of coupled ocean-atmosphere(-vegetation) simulations during the Mid- Holocene (ca. ~6 ka) in the second phase of the Paleoclimate Modeling Intercomparison Project (PMIP2) suggests a northward displacement of the ITCZ at ~6 ka (Braconnot et al., 2007) in response to increased summer insolation (Braconnot et al., 2000). This northward migration increased the mean simulated precipitation over the northern edge of the ITCZ (Braconnot et al., 2007), but could have decreased the mean precipitation simulated over its southern edge, as in northwestern Madagascar (this study).

5.3.2. Linkages to ocean-atmosphere dynamics: ITCZ and global cooling/warming conditions

Besides insolation, the ITCZ's length of visit in either hemisphere also depends on global cooling/warming conditions (e.g. Chiang and Bitz, 2005; Broccoli et al., 2006). Global cooling and/or warming conditions are often reflected by the extent of glacial advances (e.g. Fig. 3 of Wanner et al., 2011). Model simulations using an AGCM– slab ocean model (Chiang and Bitz, 2005) suggest a southward shift in the ITCZ over all tropical ocean basins when extratropical cooling and enhanced sea-ice cover in the NH were imposed. Similar simulations revealed a northward shift in the ITCZ when a southern extratropical cooling was imposed, enhancing cooling in the SH (Broccoli et al., 2006). It has therefore been reported and widely agreed that the ITCZ's latitudinal migration is driven by the temperature gradient between the two hemispheres (Chiang and Bitz, 2005; Broccoli et al., 2006; Chiang and Friedman, 2012). The ITCZ moves from a cold hemisphere towards a warmer one (e.g. Kang et al., 2008; McGee et al., 2014; Talento and Barreiro, 2016), and this latitudinal migration has been the main driver of rainfall availability in tropical and semi-arid regions visited by the ITCZ at decadal to millennial scales (e.g. Haug et al., 2001; Voarintsoa et al., 2016).

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Figure 6a suggests that deposition of Stalagmite ANJB-2 and MAJ-5 during the MEHI and the MLHI, i.e. the wetter interval, coincided with the timing of a southward migration of the ITCZ, when the NH was cooler than the SH (Marcott et al., 2013). This timing of southward migration of the ITCZ coincided with intervals of global cooler conditions with high number of glacial advances (Figs. 6b–c; Wanner et al., 2011). This scenario agrees well with the model of Chiang and Bitz (2005), and the climatic responses are very similar to what has been observed in northeastern Namibia (e.g. Voarintsoa et al., 2016). In contrast, the hiatus in deposition during the mid-Holocene, marking the Malagasy mid-Holocene dry period, was coeval with a warmer NH and cooler SH, suggesting a northward migration of the ITCZ. This scenario agrees with the model simulation of Broccoli et al. (2006).

5.3.3. ITCZ and AMOC: southward migration of the ITCZ during the 8.2 ka event

Understanding the Atlantic Meridional Overturning Circulation (AMOC)'s influence on Madagascar's hydroclimate could complete gaps in understanding the global circulation, particularly in the SH. The AMOC, a component of the Thermohaline Circulation (THC) or the Global Ocean Conveyor (Stommel, 1958; Gordon, 1986; Broecker, 1992, 1992; Delworth et al., 2008), is an important component of the Earth's climate system (Broecker 1991, 1992; Weaver et al. 1999; Delworth et al., 2008). It plays an essential role in maintaining global climate by transporting a large amount of heat from northern high latitude regions, starting for example at the North Atlantic Deep Water (NADW), to several regions worldwide (e.g., Broecker 1992; Weaver et al. 1999). It connects localized high latitude sinking cold water in north Atlantic with tropical climate changes (e.g., Dong and Sutton 2002; Zhang and Delworth 2005). The AMOC was used to interpret the non-orbital periodicity (i.e. at millennial scale) of isotopic records, identified in ice cores, as a result of an abrupt influx of meltwater from the Laurentide ice sheet into the N. Atlantic Ocean (e.g. Alley et al., 1997; Barber et al., 1999).

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 of 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, a significant short-lived cooling of the early Holocene (Alley et al., 1997), revealed in northwestern Madagascar records as a wet interval (Figs. 3 and 7), is an ideal timeframe to investigate such "ocean-land-atmosphere" relationship during the early Holocene. 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. This perturbation of the North Atlantic could partially or completely weaken the AMOC (e.g., Vellinga and Wood 2002; Dong and Sutton 2002, 2007; Dahl et al. 2005; Zhang and Delworth 2005). Weakening of the AMOC would result in a deepening of the thermocline level (Timmermann et al, 2005), which could eventually lead to an anomalous warming of the southern oceans.

In parallel to this, the weakening of the AMOC would result in a positive cooling feedback to NH regions because the Gulf Stream was shut down. This weakening of the AMOC would therefore cause a significant temperature gradient between the two hemispheres, with a cooler NH and warmer SH, suggesting a southward migration of the ITCZ during the 8.2 ka event. Thus, northwestern Madagascar become wet, as suggested by the more negative stalagmite δ^{18}O and δ^{13}C values around the 8.2 ka event. This wetting could correspond to a stronger Malagasy monsoon during austral summers, a phenomenon identical to the South American Summer Monsoon, identified in Brazil (e.g. Cheng et al., 2009). In contrast, regions in the northern Hemisphere 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).

6. Conclusion

Petrography, mineralogy, and stable isotope records from Stalagmite ANJB-2, from Anjohibe Cave, and Stalagmite MAJ-5, from Anjokipoty Cave, all combine to suggest three distinct intervals of climatic change in Madagascar during the Holocene: a wet Malagasy early Holocene interval, a dry Malagasy mid Holocene interval, and a wet Malagasy late Holocene interval. The timing of stalagmite deposition during the Malagasy early and late-Holocene in northwestern Madagascar could be attributed to a more southward migration and/or an expanded ITCZ, increasing the duration of the summer rainy seasons and/or strengthening the intensity of the Malagasy monsoon. This could have been tied to insolation, the temperature gradient between the two hemispheres, and weakening of the AMOC. In contrast, the hiatus of deposition during the mid-Holocene, here named the Malagasy mid-Holocene dry period, could reflect a northward migration of the ITCZ, leading to drier conditions in northwestern Madagascar. The evidence of the 8.2 ka event in the Malagasy records further suggests a strong link between paleoenvironmental changes in Madagascar and abrupt climatic events in the Northern Hemisphere records, suggesting that Madagascar climate was also very sensitive to such abrupt climate events.

Author Contribution

N.R.G.V. conceived the research and experiments. N.R.G.V, G.K, A.F.M.R, and M.O.M.R did the fieldwork and collected the samples. X.L., G.K., H.C., R.L.E, and N.R.G.V contributed to the ^{230}Th dating analyses. N.R.G.V provided detailed investigation of the two stalagmites, provided stable isotope measurements, prepared thin sections, and conducted X-ray diffraction analyses. G.K. also assisted with the isotopic measurements on Stalagmite ANJB-2. N.R.G.V. wrote the first draft of the manuscript and led the writing. L.B.R. provided a thorough review of the draft. N.R.G.V. and L.B.R. discussed and revised the manuscript, with additional comments from G.A.B and L.W. N.R.G.V revised the paper with input from all authors.

Competing Interests

The authors declare no conflict of interest.

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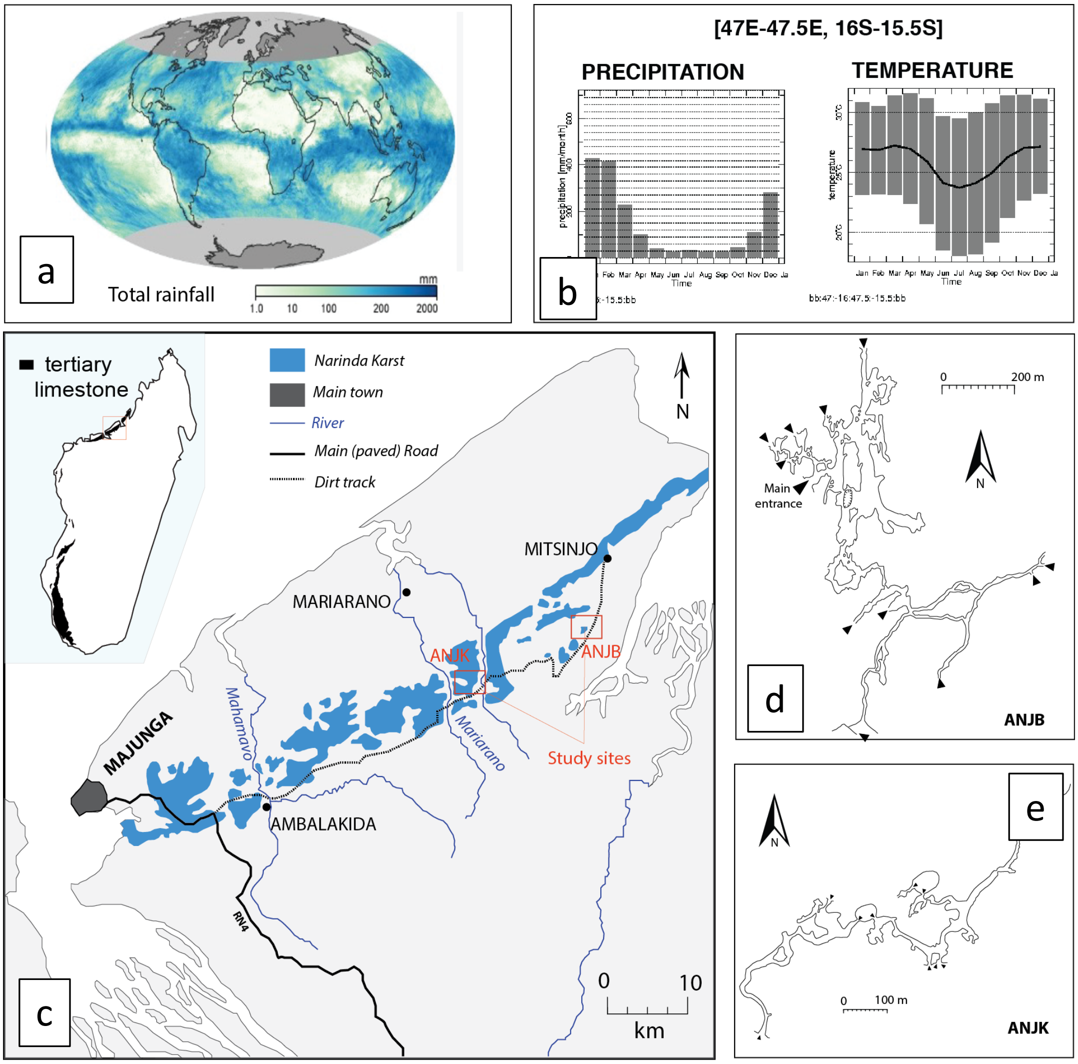

Figure 1: **Climatological and geographic setting of Madagascar and the study area**. (a) Global rainfall maps recorded by NASA's Tropical Rainfall Measuring Mission (TRMM) satellite showing the total monthly rainfall in millimeters and the overall position of the ITCZ during November, 2006. Darker blue shades indicate regions of higher rainfall (source: NASA Earth Observatory, 2016). (b) Barplots of the monthly climatology of precipitation, and the monthly average of daily maximum, minimum, and mean temperature in northwestern Madagascar. The base period used for the climatology is 1971-2000. Source: http://iridl.ldeo.columbia.edu/ (accessed August 31, 2016). (c) Simplified map showing the southwest part of the Narinda karst and the location of the study areas. Inset figure is a map of Madagascar showing the extent of the Tertiary limestone cover that makes up the Narinda karst. (d-e) Maps of Anjohibe (ANJB) and Anjokipoty (ANJK) caves (St-

Ours, 1959; Middleton and Middleton, 2002). See Figs. S1–S3 for additional information about the study locations.

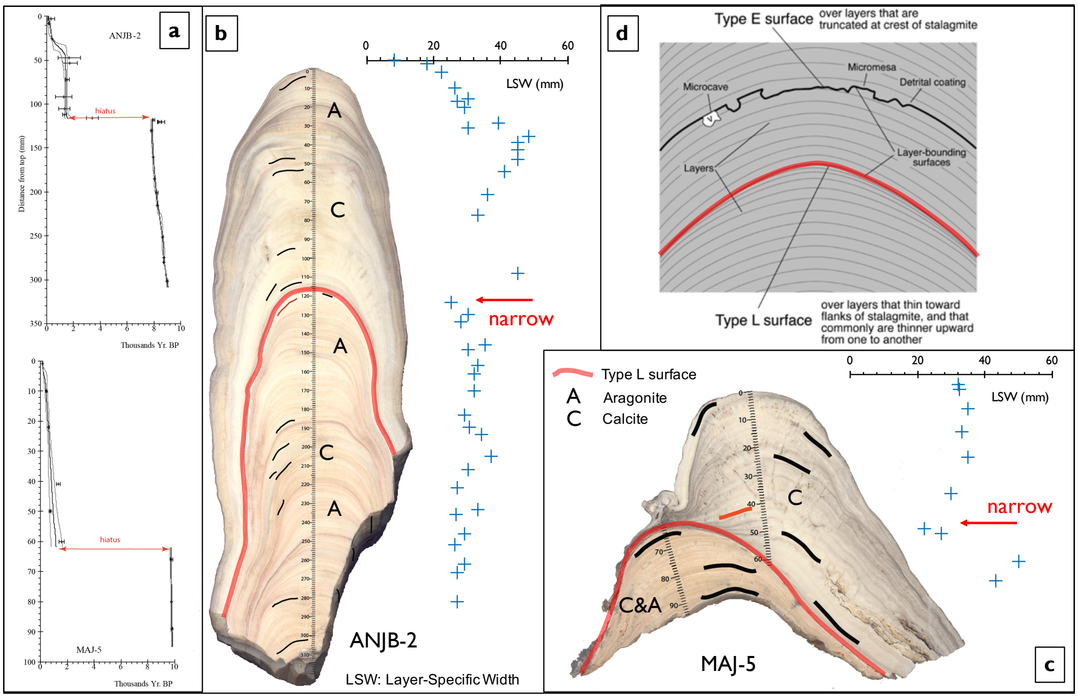

Figure 2: **Age model and petrography/mineralogy of Stalagmite ANJB-2 and MAJ-5**. a) Age model constructed using the StalAge1.0 algorithm of Scholz and Hoffman (2011) and Scholz et al. (2012). b) Scanned image of Stalagmite ANJB-2 and the corresponding variations in layer-specific width (LSW). c) Scanned image of Stalagmite MAJ-5 and the corresponding layer-specific width (LSW). d) Sketches of typical layer-bounding surfaces (Type E and Type L) of Railsback et al. (2013). X-ray diffraction data are available in Fig. S5. Close-up of photographs of the hiatuses are shown in Fig S6.

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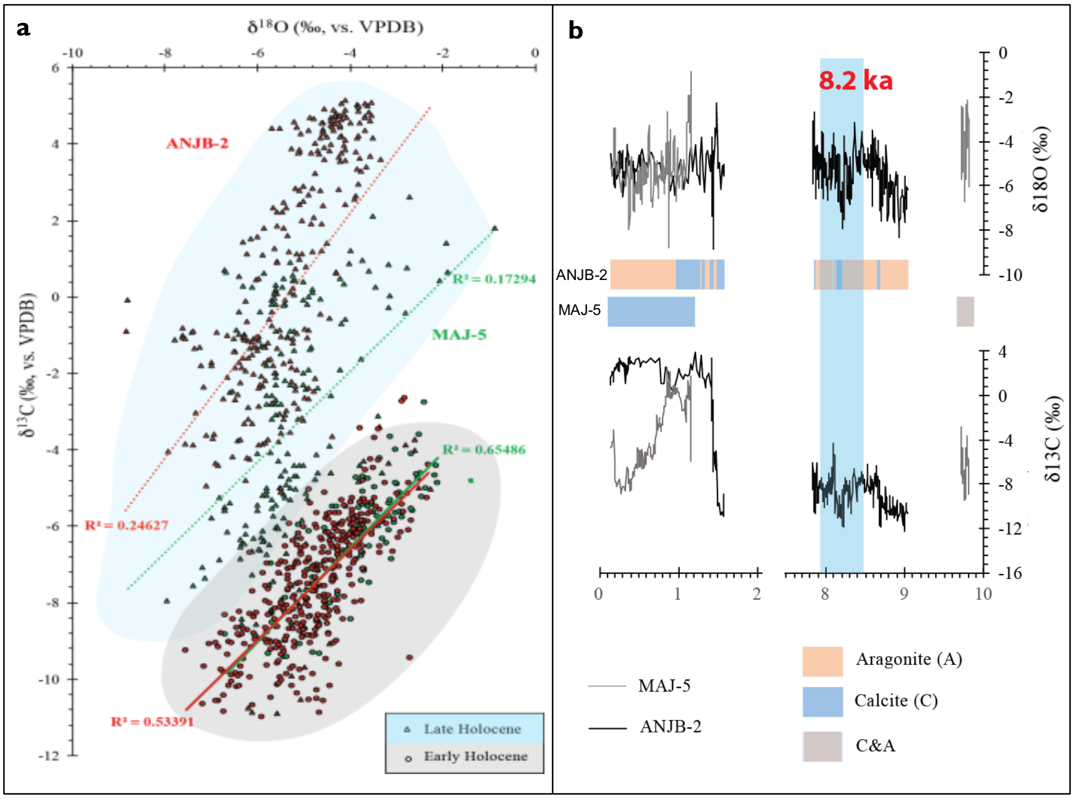

Figure 3: **Stable isotope data**. a) Scatterplots of $\delta^{13}C$ and $\delta^{18}O$ for Stalagmite MAJ-5 (green) and ANJB-2 (red) during the Malagasy early Holocene interval (circle) and the Malagasy late Holocene interval (triangle). The plot shows distinctive early and late Holocene (roughly highlighted in gray and light blue shade, respectively). b) Stable isotope of oxygen and carbon profile of Stalagmite ANJB-2 and Stalagmite MAJ-5 with their corresponding mineralogy. More information about the late Holocene is presented in Fig. S7.

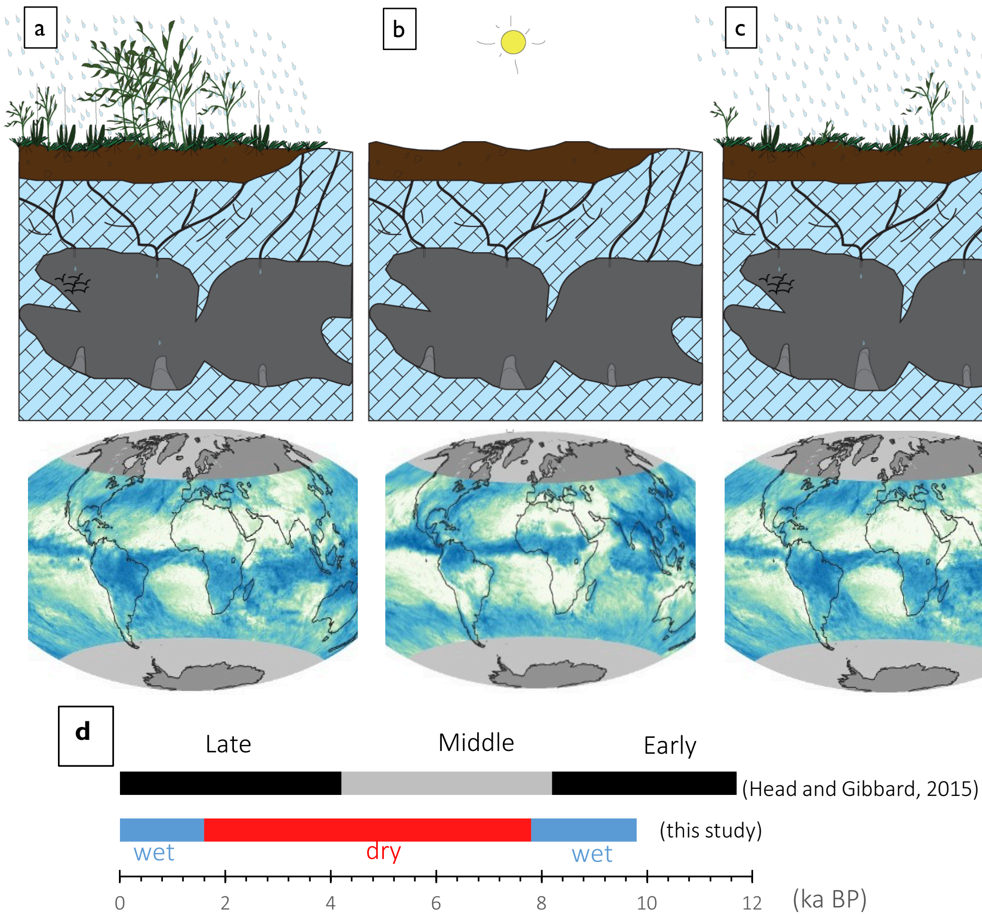

Figure 4: **Very simplified series of models portraying the Holocene climate change in northwestern Madagascar and the possible climatic conditions linked to the ITCZ**. a) Wetter conditions during the early Holocene with ITCZ south (prior to ca. 7.8 ka), favorable for stalagmite deposition. b) Drier mid-Holocene with ITCZ north with no stalagmite formation. c) Wetter conditions during the late Holocene (after ca. 1.6 ka) with ITCZ south, favorable for stalagmite deposition. For details about paleo-vegetation reconstruction, refer to Sect. 5.2 and Fig. S7. Drawings are not to scale. The bottom figures are from the same source as Fig. 1a, and they are only used here to give a perspective of the possible position of the ITCZ during the early, mid, and late Holocene. d) Comparison of the three Malagasy Holocene interval with the Head and Gibbard (2015) subdivision (see text for details, Sect. 5.2).

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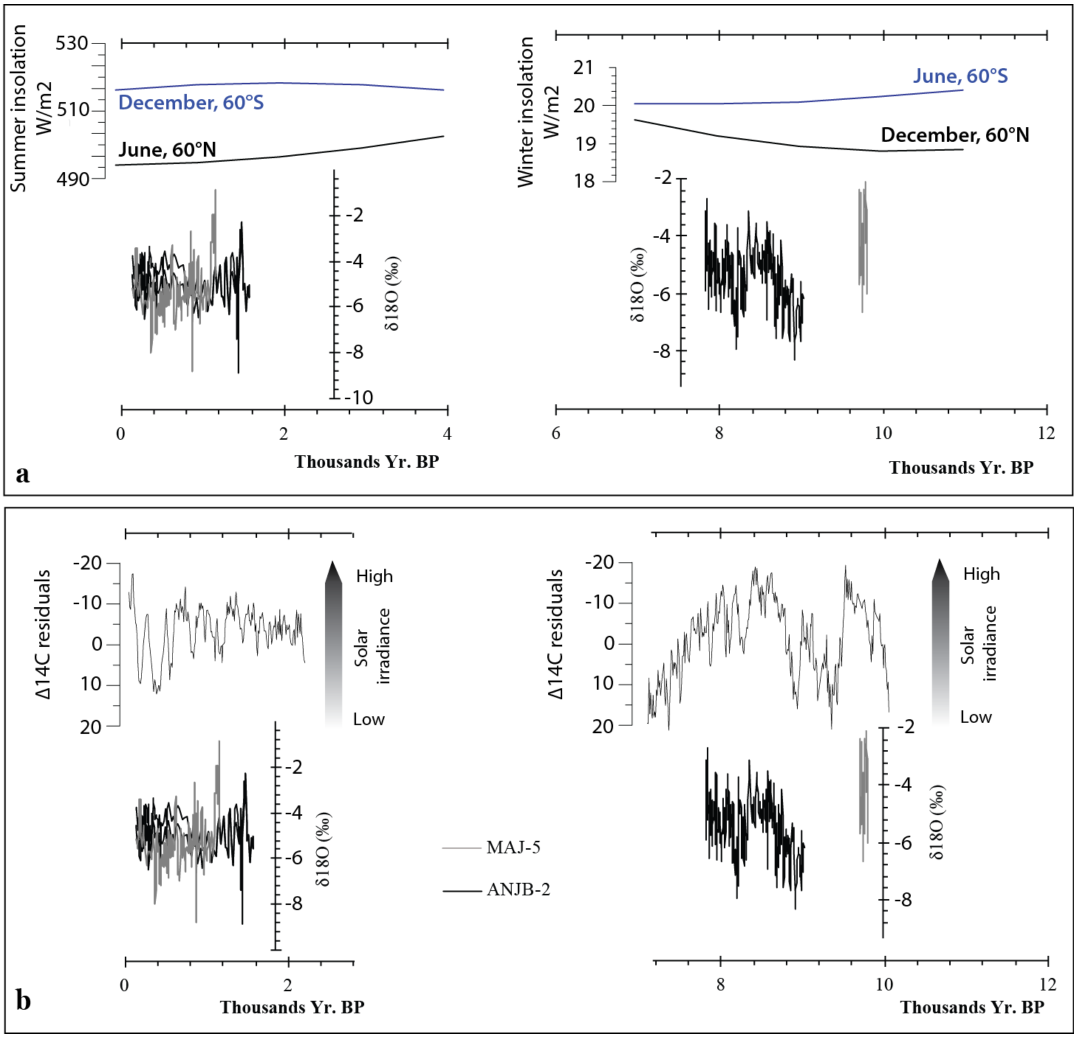

Figure 5: **Paleoclimate of northwestern Madagascar compared with insolation**. (a) Comparison between insolation curves (Berger and Loutre, 1991) and stalagmite $\delta^{18}O$. Timing of stalagmite deposition is coeval with high southern hemisphere winter insolation during the early Holocene and high southern hemisphere summer insolation during the late Holocene. (b) Reconstructed solar irradiance from $\Delta^{14}C$ residuals (Stuiver et al., 1998) compared with Stalagmite $\delta^{18}O$. Stalagmite $\delta^{18}O$ relates well to the reconstructed solar irradiance ($\Delta^{14}C$), particularly during the early Holocene.

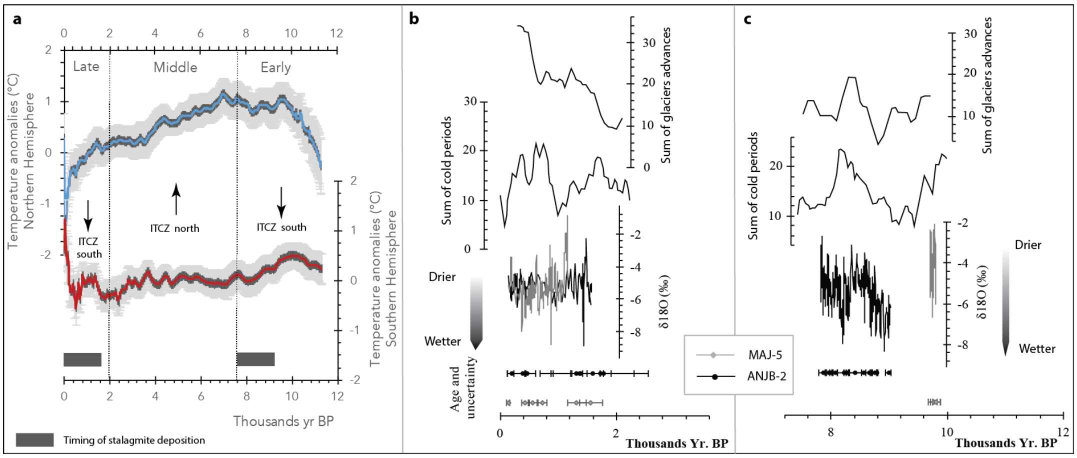

Figure 6: **Climate of NW Madagascar compared with global temperature conditions**. a) Average Holocene temperatures in the Northern Hemisphere 90°–30°N (blue) and the Southern Hemisphere 90°–30°S (red), referenced to the 1961–1990 mean temperature (Marcott et al., 2013), with 1σ uncertainty (gray). b–c) Curves representing the sum of glaciers advances from a set of global Holocene time series compiled from natural paleoclimate archives (Wanner et al., 2011) and curves representing the sum of cold periods from a set of global Holocene time series compiled from natural paleoclimate archives (Wanner et al., 2011) compared with the $\delta^{18}O$ profile of Stalagmite ANJB-2 (black) and MAJ-5 (gray) and their corresponding radiometric age data with the 2σ error.

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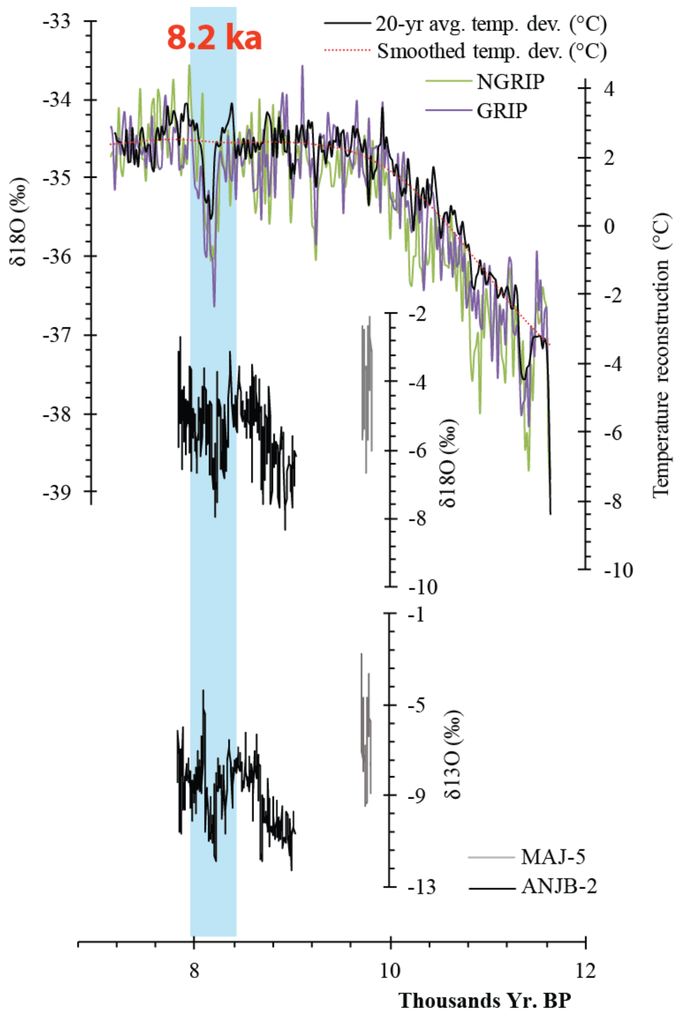

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880 Figure 7: **The 8.2 ka event in Madagascar**. Oxygen isotope record from Greenland (GRIP and NGRIP)
881 ice cores (Vinther et al., 2009) compared with Stalagmite ANJB-2 $\delta^{18}O$ and $\delta^{13}C$. Fig. S8 provides
882 additional supporting evidence of the wet 8.2 ka event.