The Malagasy monsoon over the Holocene: A review from speleothem $\delta^{18}O_c$ records

Ny Riavo G. Voarintsoa
Department of Earth and Environmental Sciences, KU Leuven, B-3001 Leuven, Belgium
Current address: Department of Earth and Atmospheric Sciences, University of Houston, Texas 77204, USA
E-mail: ngvoarin@central.uh.edu

Abstract

Speleothem stable oxygen isotope records ($\delta^{18}O_c$) are among fundamental proxies in paleoclimate reconstruction. Most generally, speleothem $\delta^{18}O_c$ reflects the $\delta^{18}O_w$ of the feeding drip water, which in turn is closely linked to the $\delta^{18}O_w$ of the water seeping into the cave that mainly originates from atmospheric precipitation. The $\delta^{18}O$ of atmospheric precipitation could in turn reflect the $\delta^{18}O$ of the vapor source (the “moisture source effect”), the distance of transport from the source (the “continent effect” resulting from Rayleigh distillation), the amount of precipitation (the “amount effect”), and the atmospheric temperature during precipitation (the “temperature effect”). This chain of relationships between various components, from the cave to the atmosphere, could explain the strength of speleothems in recording reliable information about past climate.

This paper reviews the potential of speleothem $\delta^{18}O_c$ from Anjohibe Cave, in northwestern Madagascar, to record information about its past climate, starting from reporting on the modern cave investigation on speleothem $\delta^{18}O_c$, drip water $\delta^{18}O_w$ and temperature to understanding the overall monsoonal behavior in the island, which is currently known as the driver of seasonality in Madagascar, mainly in its western part. A review is also presented of the challenges in interpreting speleothem records that may rely on the uncertainties of radiometric dating and interpretations of the paleo-records that may be different from current environmental and climatic conditions.

Key words: Malagasy monsoon, speleothems, stable oxygen isotopes, Holocene, paleoclimate

Résumé détaillé

Les enregistrements des isotopes stables d’oxygène dans les spéléothèmes ($\delta^{18}O_c$) sont parmi les proxys fondamentaux dans la reconstruction du paléoclimat. Plus généralement, le $\delta^{18}O_c$ reflète la $\delta^{18}O_w$ de l’eau au goutte-à-goutte, qui est à son tour étroitement liée au $\delta^{18}O_w$ de l’eau s’infiltrant dans la grotte qui provient principalement des précipitations atmosphériques. Les $\delta^{18}O$ des précipitations atmosphériques pourraient à leur tour refléter les $\delta^{18}O$ de la source de vapeur (l’effet de la source d’humidité), la distance de transport de la source (“l’effet continent” résultant de la distillation de Rayleigh), la quantité de précipitations (l’effet de quantité) et la température atmosphérique pendant les précipitations (l’effet de température). Cette chaîne de relations entre diverses entités, de la grotte à l’atmosphère, pourrait expliquer l’avantage des spéléothèmes en tant qu’enregistreur d’informations fiables sur le climat passé.

Madagascar est situé dans une zone sensible aux changements climatiques, particulièrement liés aux mouvements latitudinaux de la zone de convergence intertropicale (ZCIT), menant les vents de la mousson durant l’été austral dans sa partie occidentale. Il est bien connu que la position latitudinale moyenne de la ZCIT peut se déplacer vers le nord ou vers le sud en fonction du gradient de température entre l’Hémisphère Nord et l’Hémisphère Sud. Ces déplacements non saisonniers ont été démontrés par des modèles climatologiques et des données paléoclimatologiques et présentent des impacts sur les forces de la mousson, comme le cas de la Mousson Malagasy.

Cet article vise à examiner le potentiel du $\delta^{18}O_c$ extrait des spéléothèmes de la grotte d’Anjohibe, dans le Nord-ouest de Madagascar, pour enregistrer des informations sur son climat passé, à partir de rapports sur l’enquête moderne des grottes sur le $\delta^{18}O_c$ du carbonate, le $\delta^{18}O_w$ de l’eau d’infiltration et de sa température, pour comprendre le comportement global de la mousson dans l’île, qui est actuellement connu comme le moteur de la saisonnalité à Madagascar, principalement dans sa partie Ouest.

Afin de mieux mettre en évidence cette étude dans un bon contexte, cet article (1) donne un aperçu de base de la saisonnalité du climat à Madagascar, (2) discute les différents facteurs pouvant influencer la signature isotopique des précipitations, soit

Voarintsoa, N. R. G. 2021. The Malagasy monsoon over the Holocene: A review from speleothem $\delta^{18}O_c$ records, eds. K. Douglass, L. R. Godfrey & D. A. Burney. *Malagasy Nature*, 15: 56-78.

localement, soit globalement, et (3) donne un aperçu de ce que sont les spéléothèmes et de ce que leur δ$^{18}O_c$ pourrait représenter. Au-dessus de tout cela, les informations modernes issues de la surveillance des grottes suggèrent que le fractionnement isotopique obtenu dans la grotte d'Anjohibe, où les données isotopiques sont reportées, s'inscrit bien dans la courbe de fractionnement globale en fonction de la température.

Un large examen des enregistrements δ$^{18}O_c$ de chaque stalagmite publiée de la grotte d'Anjohibe suggère que l'hydroclimat de la région est relativement stable, avec une grande partie des valeurs de δ$^{18}O_c$ variant entre -4,0 et -6,0 ‰, par rapport à VPDB (Vienna-Pee Dee Belemnite), à l'exception de l'évènement 8.2 ka et d'autres intervalles de l'Holocène moyen. Cela pourrait refléter une visite plus ou moins cohérente de la ZCIT sur l'île.

L'article tente également de passer en revue les difficultés d'interprétation des enregistrements, qui peuvent reposer sur les incertitudes des datations radiométriques et des interprétations des paléo-enregistrements qui peuvent être différentes des conditions environnementales et climatiques actuelles.

Mots clés : Mousson Malagasy, spéléothèmes, isotopes stables d'oxygène, Holocène

Introduction

Climate and environmental changes are well known to significantly impact human life. In low and middle-income regions, such as Africa and Madagascar, climate change has greatly influenced the rate of human mortality, morbidity, and other health related issues (Heath, 2010; Hondula *et al*., 2012), and a slight increase (~0.2 to 0.8ºC) in temperature might negatively impact the agricultural activity in some regions (Sarr, 2012). This could be, for example, the case for many regions in south and southwestern Madagascar, which suffer from a lack of access to safe water resources (UNICEF, 2019). Extensive drought causes negative impacts on food production and human welfare worldwide (Cane *et al*., 1994) and decreases political stability (Benson & Clay, 1998). Humans are not the only ones affected by climate change, but also fauna and flora, particularly endemic species (Thuiller *et al*., 2006; Barrett *et al.,* 2013) and coral reefs (Bruggemann *et al*., 2012). They are significantly threatened by the change in their habitat and ecosystems. This requires better prediction and understanding of the future of climate and environmental changes, which is partly possible with a better understanding of past changes in climate. Some of these changes may be linked to major climatic phenomena, such as the monsoon and the inter-tropical convergence zone (ITCZ), and hence an understanding of the past dynamics of these climatic phenomena can be a key to better predict their likely behavior in the future.

Knowing what has happened in the past can be a powerful tool to better predict the likely state of climate in the future. Our understanding of past climate changes depends on linking together paleoclimate records from several locations worldwide to test and evaluate climate models (Comas-Bru *et al*., 2019). Over the past decades, well constrained laboratory experiments have also been performed to calibrate proxies to understand better natural changes (Kim & O'Neil, 1997; Hansen *et al*., 2019). This is particularly relevant for paleoclimate and paleoenvironmental reconstruction, using stalagmites as one example (Day & Henderson, 2011; Hansen *et al*., 2019). Stalagmites, a form of speleothems (= secondary cave deposits), are considered reliable geological archives in paleoclimate reconstruction (Fairchild & Baker, 2012; Wong & Breecker, 2015) because they can be accurately dated using the U-Th technique (Edwards *et al*., 1987). Additionally, stable isotope proxies, mainly of oxygen, have produced very high-resolution temporal records, yielding greater details about paleoclimate and paleoenvironment (McDermott *et al*., 2001; Fleitmann *et al*., 2004a; Boch *et al*., 2009).

Madagascar holds a key position in the Indian Ocean, and could fill gaps in understanding global climate changes by understanding its monsoonal responses to the latitudinal migration of the ITCZ. In fact, Madagascar is seasonally visited by the ITCZ and experiences monsoon during austral summer, and it hosts caves that store valuable information about its environment throughout history. It is indeed a natural laboratory to study paleoclimate and paleoenvironment, and results from investigating speleothems from this island can advance knowledge in better understanding the dynamics of the tropical rain belt and the associated monsoonal responses.

This paper will review the potential of speleothem δ$^{18}O_c$ from Anjohibe Cave to record information about its past climate. The review begins with a general introduction of the monsoon and the ITCZ as a global system, followed by a review of the climate seasonality in Madagascar and the drivers of its rainfall δ$^{18}O_w$, which is assumed to be reflected in the cave drip water $\delta^{18}O_w$ that is ultimately recorded in speleothems at the time of its formation. It is also important to provide a brief overview of the usefulness of speleothems at recording environmental and climate changes, with a greater emphasis on the carbonates $\delta^{18}O_c$ signals. Because speleothem $\delta^{18}O_c$ strongly depends on the temperature at which it grows and the drip water $\delta^{18}O_w$ from which it precipitates, this review will also report on a recent investigation performed in Anjohibe Cave. Such investigation mainly includes measurement of speleothem $\delta^{18}O_c$, drip water $\delta^{18}O_w$, and temperature to understand isotopic fractionation. Information about this isotopic fractionation is crucial to ensure that speleothems' $\delta^{18}O_c$ are reliable recorders of past climate change. With this knowledge, the available speleothem $\delta^{18}O_c$ data published from Anjohibe Cave are compiled to deduce a more comprehensive understanding of the overall monsoonal behavior in the island. The monsoon is currently known as the driver of seasonality in Madagascar, mainly in its western part. This paper will also attempt to review the challenges in the interpretation of the records, which may rely on the uncertainties of radiometric dating and interpretations of the paleo-records that may be different from current environmental and climatic conditions.

Monsoon and the Inter-Tropical Convergence Zone (ITCZ)

Both the monsoon and the ITCZ play an important role in global atmospheric heat and moisture transport (Berger, 2009; Basha *et al*., 2015). Understanding the monsoon strength is fundamental in understanding the dynamics of the ITCZ, and vice versa, and this is additionally crucial in understanding the atmospheric circulation at global scale.

Etymologically, the word "monsoon" comes from the Arabic word *mawsim* which means seasons (Berger, 2009), and it was defined as a seasonal reversal in wind direction of the near-surface wind (Trenberth *et al*., 2000; Wang, 2009). Monsoons are generally driven by the thermal difference between continents, such as the Eurasian continent, and oceans, such as the Indo-Pacific Ocean. Satellite and conventional observations additionally suggest that the monsoon is a manifestation of seasonal migration of the ITCZ (Gadgil, 2003; Wang, 2009), suggesting its global nature. This means that the monsoon is a global system and it occurs in all continents, except in Antarctica (Wang, 2009).

The global monsoon system comprises six main regions (Figure 1), including the North American monsoon, the South American Monsoon, the South African Monsoon, the North African Monsoon, the Asian Monsoon, and the Australian-Indonesian Monsoon (Wang & Ding, 2008; Wang, 2009), the well-known among which combines the Africa-Asia-Australia monsoon. The monsoon in Madagascar belongs to the South African Monsoon, but it is closely influenced by changes in the Asian Monsoon regions (Wang & Ding, 2008; Figure 1). Understanding the monsoon strength is crucial in understanding the atmospheric circulation at global scale not only at short time scale but at scales beyond human presence on Earth. Madagascar has a potential to play a key role in understanding the monsoon system at these different time intervals.

The ITCZ, also known by sailors as the "doldrums," is a zone of low pressure near the equator, where two easterly trade winds originating from the northern

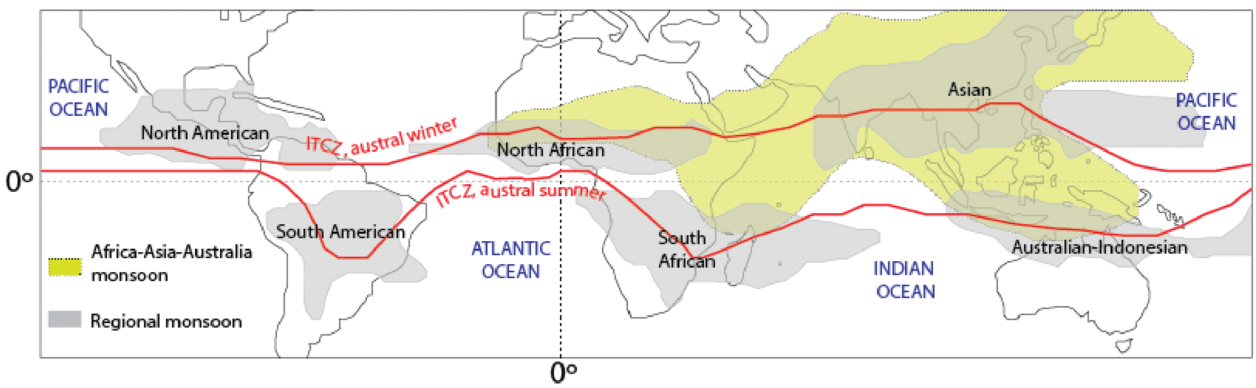

Figure 1. Schematic representation of the ITCZ and monsoons. The spatial coverage of the Africa-Asia-Australia monsoon was redrawn from Black (2002). The six other regional monsoons were redrawn from Wang (2009), which was originally redrawn from Wang & Ding (2008). The two red lines represent the seasonal mean position of the ITCZ during austral winter (north) and summer (south).

hemisphere (NH) and southern hemisphere (SH) converge. The zone of convergence marks the boundary of the Hadley cell, and it is characterized by a strong upward motion of air from its lower level, forming clouds and precipitation (Figure 2). The ITCZ plays an important role in maintaining the Earth's climate (Zhang, 1993) at different timescales. It is the main driver of boreal and austral summer rainfall in the tropics and subtropics, respectively.

It is widely known that the ITCZ migrates seasonally, following the temperature gradient between the NH and the SH, which is one of the main driving factors of the ITCZ's long-term migration (Chiang & Friedman, 2012). Beyond instrumental records, changes in the relative position of the ITCZ have been investigated via climate modeling (Broccoli *et al*., 2006; Kang *et al*., 2008; Frierson & Hwang, 2012) and have been proven using paleorecords. For example, the ITCZ moves southward during extended cold periods, such as during the Last Glacial Maximum (Arbuszewski *et al*., 2013; Leech *et al*., 2013; McGee *et al*., 2014), the Heinrich stadials and the mid-Holocene (McGee *et al*., 2014), and even during the Little Ice Age (Voarintsoa *et al*., 2017a; Railsback *et al*., 2018). Beyond this latitudinal migration, researchers have also identified an expansion and contraction of this rain belt over decadal to centennial timescales in response to external forcing (Yan *et al*., 2015; Denniston *et al*., 2016; Donohoe *et al*., 2019).

Of relevance to this current paper, the latitudinal migration of the ITCZ has significantly impacted the monsoonal activities in the Asian regions, such as the monsoon megadroughts of the last millennium that are interpreted to reflect a weakening of the Indian Monsoon at the onset of the Little Ice Age (Sinha *et al*., 2011), during the southward migration of the ITCZ. Such behavior can further be assessed in Madagascar, given its strategic position relative to the ITCZ.

Climate seasonality in Madagascar

Madagascar's climate is unique because of its mountainous nature, its position in the Indian Ocean, the seasonal migration of the ITCZ, and the changes in monsoon strength. Rainfall is influenced alternatively by dry trade-wind conditions in winter (May-October) and monsoon driven tropical storms in summer (November-March). This is the main pattern of the island's rainfall seasonality.

Regionally distinct rainfall gradients from east to west and from north to south are evident across the

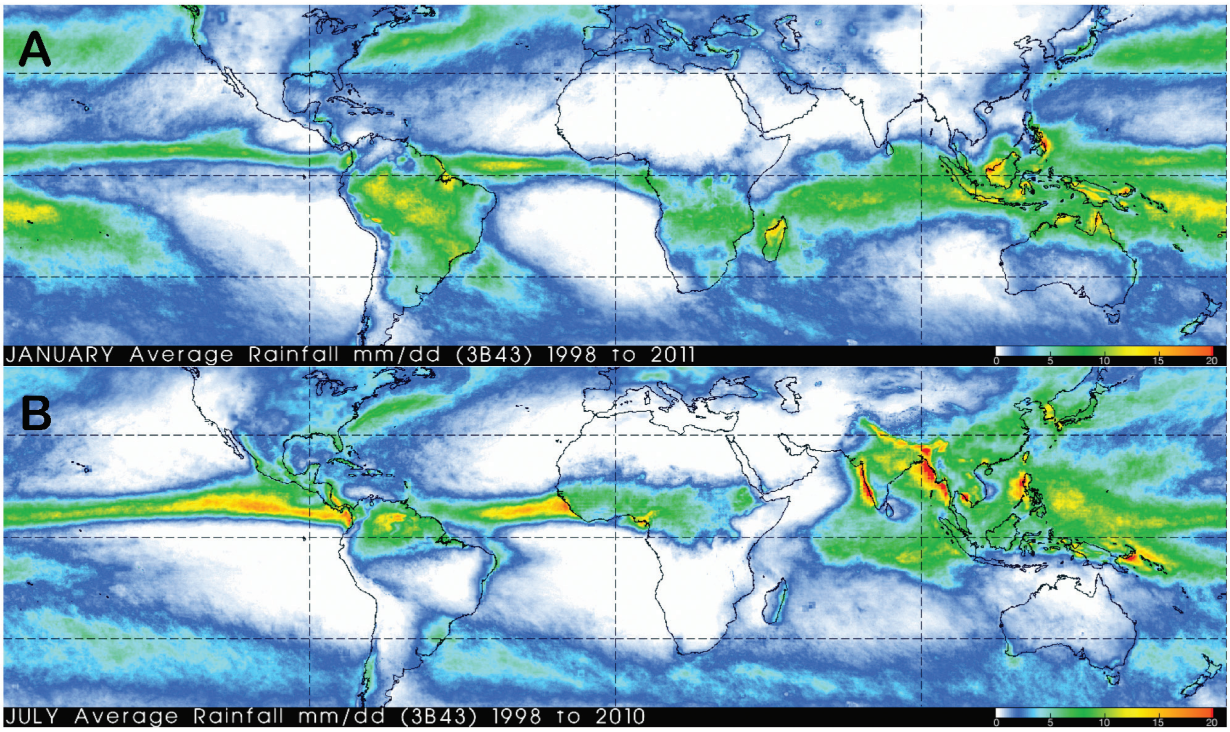

Figure 2. Global rainfall averages from 1998-2010 for (a) the month of January and (b) the month of July from the Tropical Rainfall Measuring Mission (TRMM), a joint mission of NASA and the Japan Aerospace Exploration Agency. These visualizations were generated from the 3B43 TRMM sensor algorithm. These images are the result of averaging all available Monthly 0.25° x 0.25° 3B43 merged TRMM and other sources estimate data. The images cover the globe from 40°N to 40°S. (Source: https://gpm.nasa.gov/TRMM, accessed May 2020).

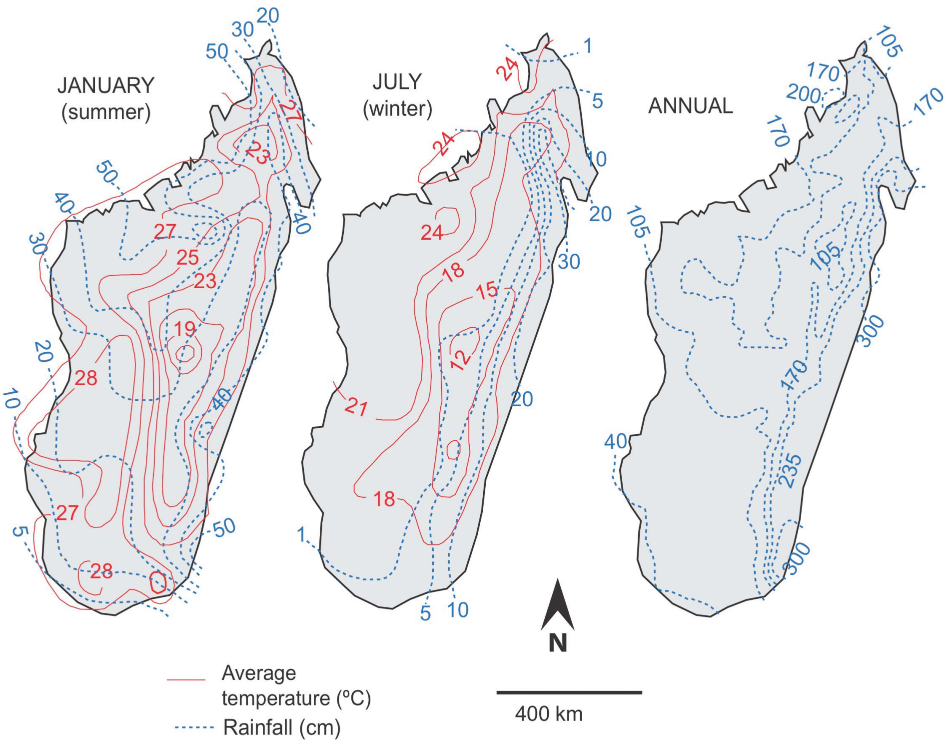

Figure 3. Maps showing the general climate (temperature and rainfall) in Madagascar (compiled from Jury, 2003; Wells, 2003). Note the north-south and east-west gradient in rainfall and temperature during summer (January) and winter (July) seasons.

entire country (Figure 3) (Jury, 2003; DGM, 2008). This gradient could be explained by the north-south mountain chain (~1200-1500 m high), which acts to split the shallow trade winds from the Indian Ocean approaching the eastern and northeastern coast of Madagascar all year long. The chain of mountains favors an orographic uplift, ensuring regular rainfall on the dense cover of tropical rainforest in northeastern and eastern parts of Madagascar, and rain shadow to the leeward side of the mountain chain. As a result, the windward sides of the mountain chain remain humid all year long, even during winter seasons (Figure 3), with a dominant tropical rainforest climate (Af) in the eastern side of the chain of mountains and relatively temperate climate (with dry winter and warm/hot summer; Csa, Cwb, Cfb, Cfa, Cwa) in the immediate western side of the chain of mountains (mainly in the Central Highlands), according to Köppen-Geiger climate classification (Rubel & Kottek, 2010).

In contrast to the northeastern and eastern parts of Madagascar, rainfall in the western and southwestern part of the island is entirely dependent on the austral summer monsoon air from the north with its high thermodynamic energy and by subtropical westerlies from the south (Jury, 2003). Austral monsoon in Madagascar is closely linked to the southward migration of the ITCZ. As a result, climate is tropical monsoon and tropical savanna (Am, Aw) in the west and is typically hot and semi-arid (BSh, BWh) in the southwest (Rubel & Kottek, 2010). Rainfall is typically recorded between November and March (Jury, 2003). The study region of interest in this paper, Mahajanga, belongs to the tropical savanna climate and with clear rainfall seasonality, i.e., dry and cool between May and October, and wet and warm between November and April (Figure 4).

Rainfall $\delta^{18}O$ in Madagascar

Potential influence of the seasonality and the island's topography

Although rainfall $\delta^{18}O$ data are limited to only one weather station in Antananarivo, the capital city of Madagascar, an assessment of discontinuous time series of monthly precipitation, monthly temperature, and the corresponding $\delta^{18}O_w$ of the available rainfall between 1961 and 1976 supports the seasonal and amount effects (Figure 5). In other words, both rainfall amount and temperature seem to influence $\delta^{18}O$ (r^2 = 0.33 and 0.35, respectively; see Voarintsoa *et al.*, 2017b), in a sense that rainfall during cooler and drier months is more enriched in ^{18}O than rainfall during warmer and wetter months. Given the current topography of Madagascar and its current

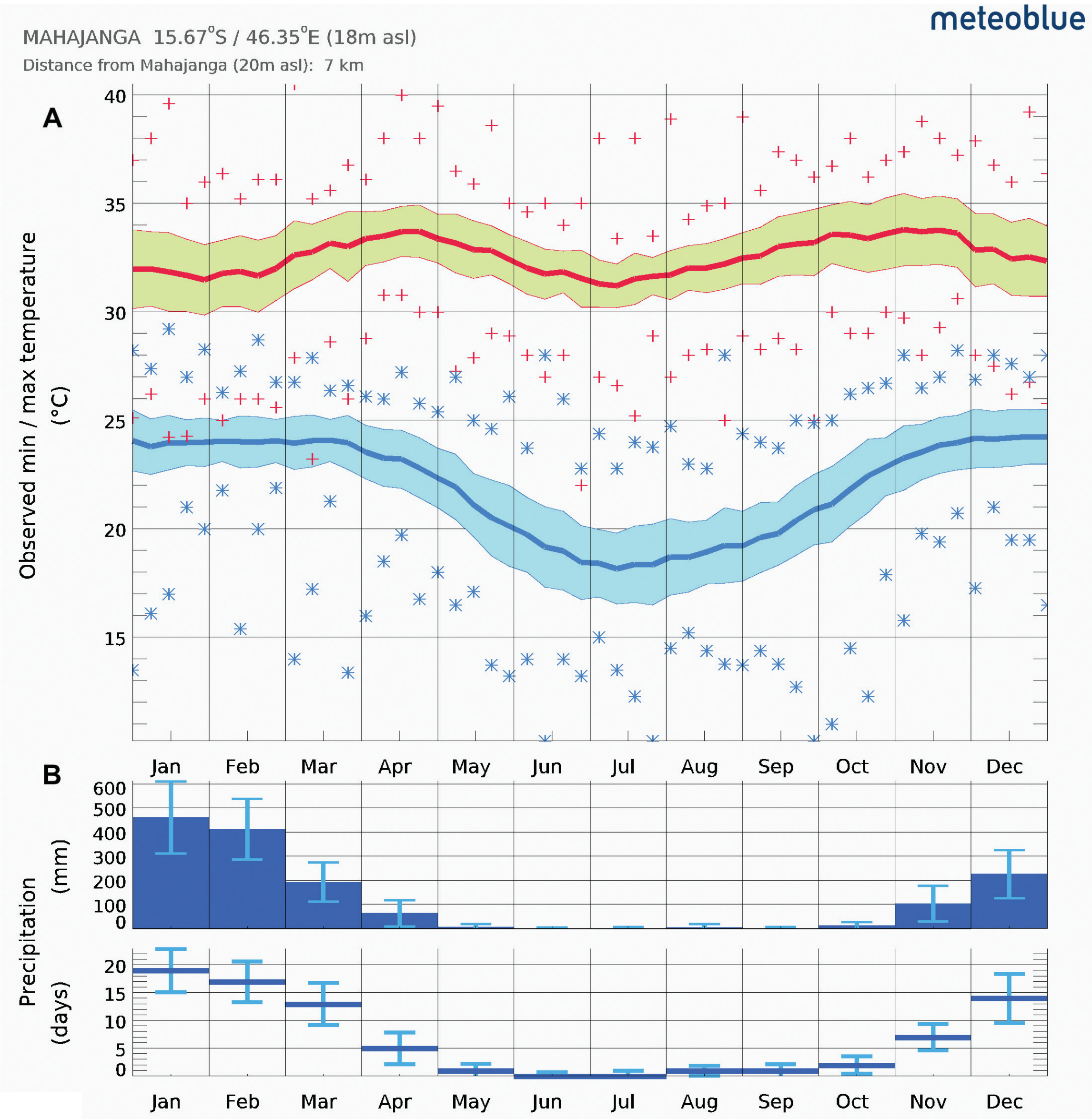

Figure 4. Meteogram climate from a weather station in Mahajanga over at least the past 10 years. **A**) Average, maximum (red) and minimum (blue) temperatures, with two thirds of the observed values highlighted within the colored temperature range. Extreme values are represented by the characters + and *, respectively. **B**) Precipitation amount (in mm) and the range of monthly means, and number of days per month with precipitation and the corresponding variations within the bars. (Source: www.meteoblue.com).

geographic position relative to the ITCZ, the seasonal variability of the island's rainfall $\delta^{18}O_w$ is assumed to be influenced closely by the "amount effect", which means more negative $\delta^{18}O_w$ during rainier months (Dansgaard, 1964; McDermott, 2004; Risi *et al.*, 2008; Lachniet, 2009). With this logic, summer rainfall should be more depleted in ^{18}O than winter rainfall.

Using the available rainfall $\delta^{18}O_w$ data from Antananarivo and other rainfall $\delta^{18}O_w$ data worldwide, it is possible to estimate the modern monthly deuterium and oxygen isotope composition of precipitation at a specific site worldwide using the Online Isotopes in Precipitation Calculator (OIPC; Bowen, 2020). Estimates are calculated from a global data set, which are derived primarily from the International Atomic Energy Association/World Meteorological Organization Global Network for Isotopes in Precipitation, according to an algorithm developed by Bowen & Wilkinson (2002) and refined by Bowen & Revenaugh (2003) and Bowen *et al.* (2005). Estimates of the modern monthly deuterium and oxygen isotope composition of precipitation at Anjohibe Cave in Mahajanga suggest an agreement of the local estimated isotopic data with the Global Meteoric Line (GMLW, $\delta D = 8 \times \delta^{18}O + 10$) and the collected drip water from the cave. Evaluation of the annual variability of the estimated rainfall isotopic data suggests an amount effect signal, i.e., more negative values during summer than during winter (Table 1, Figure 6).

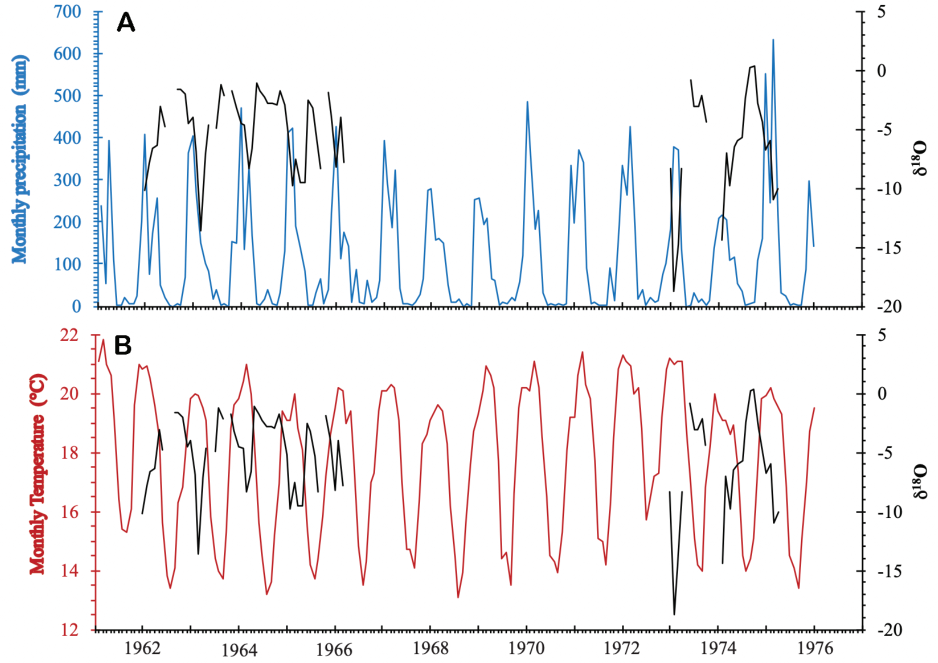

Figure 5. Time series of **A**) rainfall and $\delta^{18}O$ and **B**) temperature and $\delta^{18}O$ observed and measured from Antananarivo, Madagascar (18°54′00″S; 047°31′48″E; elevation 1300 m asl) showing that drier winter seasons are marked with higher $\delta^{18}O$ values, whereas wetter summer seasons with more negative $\delta^{18}O$. The minor ticks in the x-axis represent the twelve months of the year, starting from January (left) to December (right). Data are from IAEA/WMO (2004).

Table 1. Estimated modern mean annual and monthly deuterium and oxygen isotope composition of precipitation in Anjohibe Cave (-15.54258°S; 46.88538°E; 50 m).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
δ^2H (‰, V-SMOW)	-21	-29	-26	-5	3	-3	-3	-4	0	13	-2	-3
$\delta^{18}O$ (‰, V-SMOW)	-3.6	-4.9	-4.3	-2.2	-1	-2	-2.3	-2	-1.2	0	-1.9	-2.1

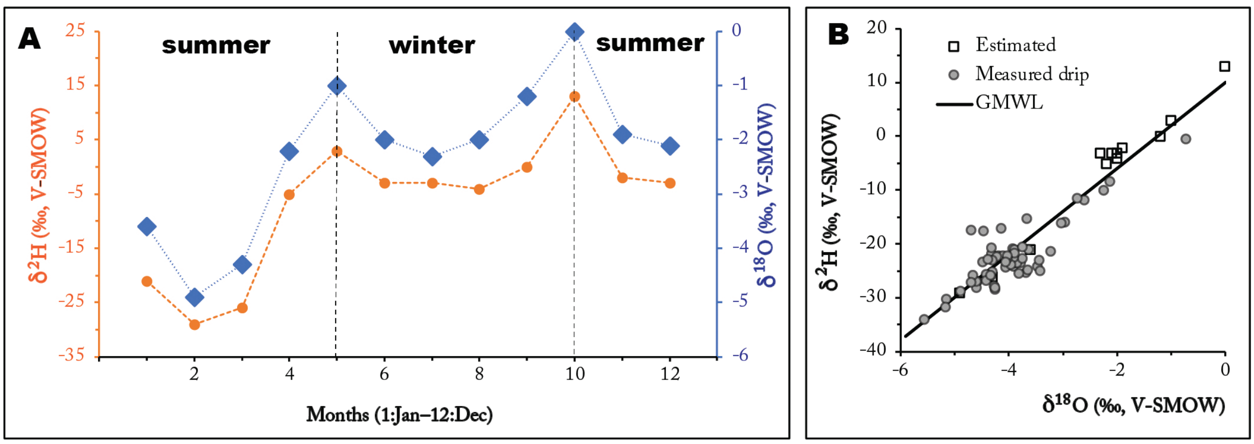

Figure 6. Estimated rainfall δD and $\delta^{18}O$ using the Online Isotopes in Precipitation Calculator (OIPC; Bowen, 2020). **A**) seasonal variability of δD and $\delta^{18}O$ showing more negative values during summer than winter. **B**) Plot of the estimated rainfall δD vs $\delta^{18}O$ and the measured drip water δD vs $\delta^{18}O$ in Anjohibe Cave compared with the Global Meteoric Water Line (GMLW, δD = 8 x $\delta^{18}O$ +10).

Potential influence of the moisture source and atmospheric circulation

The majority of moisture sources in Madagascar originate from western Indian Ocean. In addition to this, the other regions of Madagascar might receive their moisture sources either from north of the Mozambique Channel, e.g., northern, northwestern, and western Madagascar or south of the Mozambique

Channel, such as the Aghulas Current, e.g., southwestern and southern Madagascar, especially during the summer. Although not fully constrained, the values of $\delta^{18}O$ in Madagascar can vary not only as a function of seasons, but also as a function of the moisture sources and the changes that influence the $\delta^{18}O$ of the vapor sources. For example, the Indian Ocean might experience reversal in its sea surface temperature from its eastern to its western side, which is known as the Indian Ocean Dipole, or IOD (Saji *et al*., 1999). During positive IOD events, when the eastern Indian Ocean is cooler and western Indian Ocean is warmer, eastern Africa receives more rainfall (Black *et al*., 2003). IOD could also influence climate in Madagascar, and this could be reflected in the rainfall $\delta^{18}O_w$. Another example, the Aghulas Current, is strongly connected to the global conveyor belt, also known as the Atlantic Meridional Overturning Circulation, or AMOC (Broecker, 1991; Lynch-Stieglitz, 2017) or the Thermohaline Circulation (THC). The AMOC is known to influence the global climate system, particularly the millennial variability during the last deglaciation. This evidence is seen in the non-orbital periodicity (i.e. at millennial scale) of isotopic records from ice cores as a result of an abrupt influx of meltwater to the N. Atlantic Ocean (Alley *et al*., 1997; Alley & Agustsdottir, 2005). Typical events are the 8.2 ka event (Thomas *et al*., 2007), the Younger Dryas (Alley, 2000), the Heinrich events (Cacho *et al*., 1999; McGee *et al*., 2014), and the Dansgaard-Oeschger oscillations (Cacho *et al*., 1999). Any changes to the THC should significantly affect the isotopic composition in the Aghulas moisture source region, which in turn may influence the isotopic composition of rainfall originating from the southern and southwestern part of Madagascar (Zinke *et al*., 2014).

Speleothems

Speleothem minerals are highly variable but calcium carbonate, particularly calcite and aragonite, are the most abundant (Hill & Forti, 1997). Speleothems can be found in various forms (e.g., flowstones, stalactites, draperies, and stalagmites), but stalagmites are the most commonly studied in paleoclimate reconstructions because of their process of formation.

Stalagmites are upward-growing mounds of carbonate mineral deposits in caves, typically with convex floor, sub-cylindrical, and conical shape. They are fed by water dripping from an overhead stalactite, a soda straw, or simply from the cave ceiling. $CaCO_3$ precipitation occurs mainly by CO_2 degassing of the drip water, leading to an increase of its CO_3^{2-} concentration and pH (evaporation could also play an additional role, increasing its Ca^{2+} concentration). Degassing occurs because the CO_2–saturated water percolating down to the cave meets the cave air, the pCO_2 of which is relatively low compared to that of the drip water. The fundamental equation for stalagmite deposition is shown in Equation 1, and a simplified sketch describing its process of formation is shown in Figure 7. Equation 1 is maintained in equilibrium when $CO_{2(g)}$ and Ca^{2+} are proportionately in equilibrium. This equation explains that an increase in Ca^{2+} in the drip water leads to stalagmite deposition, as the water becomes supersaturated with regard to $CaCO_3$.

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

(Equation 1)

Stalagmites are considered one of the most useful paleoclimate archives because they preserve several geochemical signatures (proxies) that are directly or indirectly influenced by climate. Their potential as climate indicators was first discussed by Hendy & Wilson (1968) followed by Thompson *et al*. (1974), with a more ambitious goal in reconstructing paleotemperature, following Urey (1947). This is mainly because cave environments are quite stable and their temperature commonly reflects the regional mean annual temperature (Poulson & White, 1969). Stalagmites grow very slowly, with a growth rate of approximately a millimeter per year or less on average, and each of the deposited carbonate layers preserves various signatures that reflect the environmental conditions at the time of their deposition. By far, the most commonly collected and used proxies from stalagmites have been their oxygen isotopes, and a paleoclimate history may be established in combination with U-Th chronology (Edwards *et al*., 1987). For a more comprehensive paleoclimate reconstruction, the speleothem oxygen isotope proxy has been combined with the carbon isotope proxy and other unconventional proxies such as changes in mineralogy, the nature of the layer-bounding surfaces between stalagmite layers, and elemental chemistry (Cruz *et al*., 2007; Voarintsoa *et al*., 2017a).

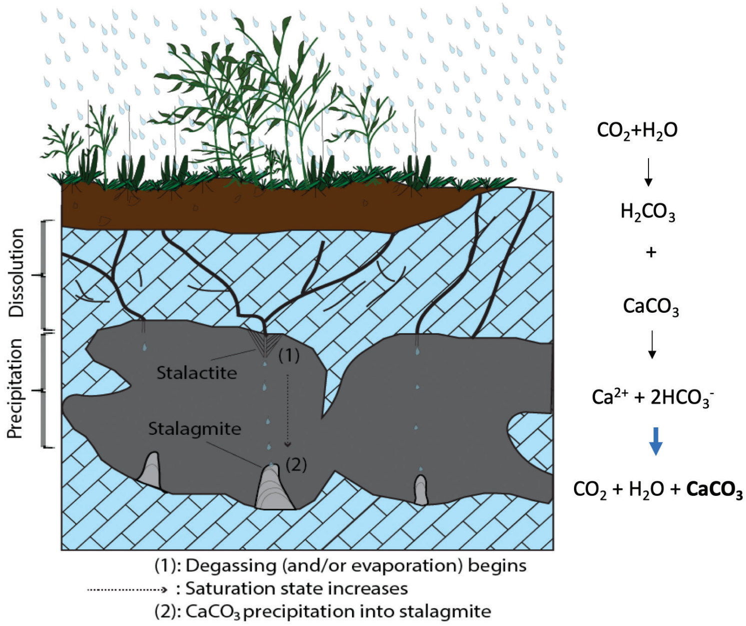

Figure 7. Generalized sketch showing the processes of stalagmite formation (from dissolution, degassing and/or evaporation of the drip water, to $CaCO_3$ precipitation to stalagmite), and the linkage between the cave system and the landscape above it. Stalactite and stalagmite are examples of cave deposits. (Source: Voarintsoa, 2017).

Speleothem $\delta^{18}O_c$ and what it could represent

Stable isotopes of oxygen, denoted $\delta^{18}O$, are among fundamental proxies used in paleoclimate studies, either in the study of coral records (Zinke *et al.*, 2014), ice core records (Thomas *et al.*, 2007), or stalagmite records (Fleitmann *et al.*, 2004a). For stalagmites, scientists originally hoped to use their $\delta^{18}O_c$ signatures as an indicator of paleotemperature, as carbonate isotopic composition is mainly controlled by two factors including temperature and $\delta^{18}O$ of the parent water (Urey, 1947; Emiliani, 1966), but later realized that $\delta^{18}O_c$ of stalagmites is controlled by a complex combination of several factors (McDermott, 2004; Lachniet, 2009). Indeed, interpretations of speleothem $\delta^{18}O_c$ time series may be quite complex. Speleothem $\delta^{18}O_c$ typically reflects the $\delta^{18}O_w$ of the feeding drip water, which in turn is closely linked to the $\delta^{18}O_w$ of the water seeping into the cave that mainly originates from atmospheric precipitation (Burns *et al.*, 2002; Fairchild & McMillan, 2007). The $\delta^{18}O$ of atmospheric precipitation could in turn reflect the $\delta^{18}O$ of the vapor source (the "moisture source effect"), the distance of transport from the source (the "continent effect" resulting from Rayleigh distillation), the amount of precipitation (the "amount effect"), and the atmospheric temperature during precipitation (the "temperature effect").

This chain of relationships between various components from the atmosphere to cave could explain the strength of speleothems in recording reliable information about past climate. For example, longer time records of oxygen isotopic variations in speleothems may be a good indicator of a change in ice volume, which could be reflected in the changes of sea level during glacial or interglacial periods (see review in McDermott, 2004; Lachniet, 2009). It is generally agreed that continental glaciation and deglaciation induce changes in the $\delta^{18}O$-value of the ocean, because thicker ice shields might concentrate ^{16}O more than smaller ones. The change in global sea level as a function of cold and warm periods can influence the $\delta^{18}O$ value of the source water (Zachos *et al.*, 2001). This can later be transferred to the $\delta^{18}O$ signals in precipitation and then to cave drip waters, from which speleothems precipitate (Lachniet, 2009).

Numerous factors such as latitude, altitude, distance from the vapor source, and seasons can also influence the change in rainfall $\delta^{18}O$, and subsequently the $\delta^{18}O$ of the cave drip waters. This means that precipitation $\delta^{18}O$ value decreases 1) from low to high latitude, 2) from low to high altitude, 3) as the water vapor travels farther from its sources (Bowen & Wilkinson, 2002; LeGrande & Schmidt, 2006). This is because heavier isotopes of oxygen (^{18}O) have a higher distribution coefficient (D>1) to solid/denser phase than the lighter isotopes ^{16}O. In tropical areas, such as Madagascar, where convective activity is strong during austral monsoon, variations in $\delta^{18}O$ could reflect the "amount effect" (Figures 5 & 6), when more negative values of $\delta^{18}O$ are interpreted to reflect wetter periods, whereas greater values for drier periods, as in other studies (Bar-Matthews *et al*., 1996; Burns *et al*., 2002; Fairchild & McMillan, 2007).

Immediate controls on $\delta^{18}O_c$ variability in speleothems include $\delta^{18}O_w$ of the drip water which could vary depending on the $\delta^{18}O_w$ of local rainfall (linked to the factors described above), the cave temperature, the rate of evaporation, and the rate of degassing inside the cave. If degassing is fast and if evaporation inside the cave is intense, these could potentially increase $\delta^{18}O_c$, as lighter oxygen isotopes (^{16}O) are removed from the drip water to the vapor in the cave atmosphere. The influence of cave temperature on $\delta^{18}O_c$ is not easily detectable in a single cave as the cave mean annual temperature is commonly stable and represents the mean annual temperature of the region. However, this could be significant at global scale when the temperature inside each individual cave is statistically different (Tremaine *et al*., 2011; Johnston *et al*., 2013), or as mentioned earlier at longer time scale when significant temperature difference is observed between two periods of time, such as during glacial and interglacial times.

Speleothem records in Madagascar

Over the past five years, at least six speleothems have produced high resolution $\delta^{18}O_c$ records from Anjohibe Cave (Figure 8) to uncover past climate and past environmental change in northwestern Madagascar, with most of the samples covering the late Holocene interval (starting ~300 yr CE to present). Among these samples, only two stalagmites (ANJB-2 and ANJ94-5) cover a longer time interval (the Holocene), with ANJB-2 recording a remarkable hiatus during the middle Holocene as evidenced by radiometric dating, petrographic features, and a white, fibrous, and porous aragonite mineralogy (Figure 8; Voarintsoa *et al*., 2017c).

Speleothem modern information

To ensure that speleothem $\delta^{18}O_c$ is a reliable recorder of past climate change, measurement of modern speleothem $\delta^{18}O_c$, drip water $\delta^{18}O_{w,}$ and temperature from Anjohibe Cave was performed to understand isotopic fractionation and to test for consistency of the speleothem isotopic records relative to global data sets (Voarintsoa *et al*., 2020a). An understanding of the processes that control such fractionation between water and carbonate species is essential for the proper interpretation of speleothem $\delta^{18}O_c$ as proxies for paleoclimate and paleoenvironment changes. This modern investigation suggests that speleothems from Anjohibe Cave precipitate out of equilibrium relative to their parent drip water if compared with their laboratory equivalent (Kim & O'Neil, 1997). Furthermore, the calculated isotopic fractionation factors between speleothem carbonates and their parent water ($^{18}\alpha_{CaCO3\text{-}H2O} = (\delta^{18}O_{c,\ VSMOW} + 1000)/(\delta^{18}O_{w,\ VSMOW} + 1000)$ fit well within the global fractionation curve as a function of temperature (Figure 9) that was first reported by Tremaine *et al*. (2011), $1000\ \ln^{18}\alpha = 16.1\ (10^3/T(°K)) - 24.6$, and followed by Johnston *et al*. (2013), $1000\ \ln^{18}\alpha =$

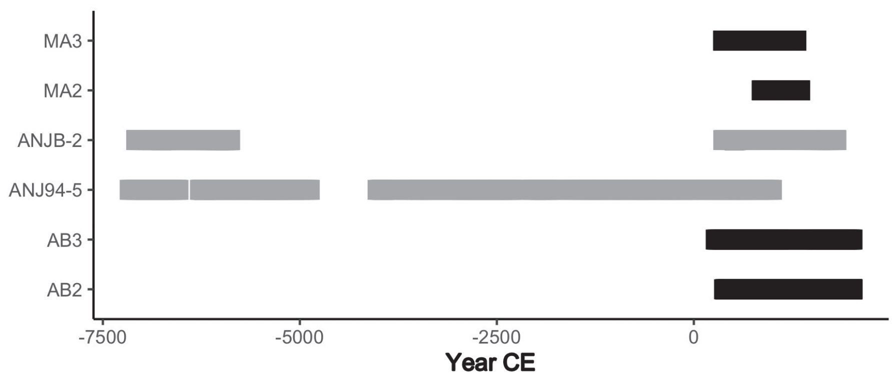

Figure 8. Time coverage of each published stalagmite $\delta^{18}O_c$. Stalagmite AB3 is from Burns *et al*. (2016). Stalagmite AB2 was first reported in Burns *et al*. (2016) and was re-analyzed by Scroxton *et al*. (2017). Stalagmite ANJ94-5 was studied by Wang *et al*. (2019). Stalagmites ANJB-2, MA2, and MA3 were studied by Voarintsoa *et al*. (2017c) and Voarintsoa *et al*. (2017b), respectively.

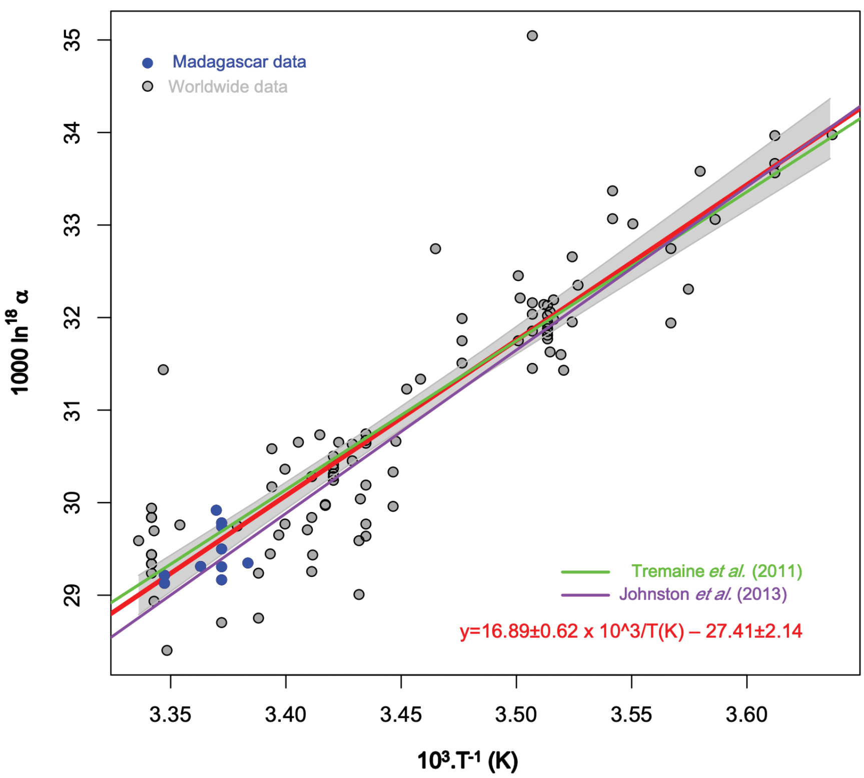

Figure 9. Global modern speleothem data showing the isotopic fractionation curves (1000 ln $^{18}\alpha$) as a function of temperature (in °K). The data from Anjohibe Cave, in Madagascar, are shown in blue circles to highlight them from the global database. Also shown for comparison are the fractionation curves of Tremaine *et al*. (2011) and Johnston *et al*. (2013).

17.66 (10^3/T(°K)) – 30.16. This global consistency confirms the general statement of Mickler *et al*. (2006), from investigating 165 published speleothem stable isotope records worldwide, that the majority of these speleothem records precipitate out of "isotopic equilibrium," a statement that is later supported by Daëron *et al*. (2019) from investigating various earth-surface calcite precipitates. Despite the yet limited understanding of the extent of kinetic isotopic fractionation in global cave studies, this general consistency of the data from Anjohibe Cave suggests the usefulness of speleothem $\delta^{18}O_c$ from Anjohibe Cave for further paleoclimate study.

Speleothem paleo-records

A broad screening of the $\delta^{18}O_c$ records of each published stalagmite from Anjohibe Cave (Figure 10) can suggest a relatively stable hydroclimate in northwestern Madagascar, with much of the $\delta^{18}O_c$ values varying between -4.0 and -6.0‰, vs. VPDB (Vienna-Pee Dee Belemnite). This could reflect a more or less consistent visit of the ITCZ to the island. However, closer examination of the speleothem records suggests changes towards wetter or drier climate over the course of the Holocene until now. Some of these changes record distinct isotopic signals, such as the 8.2 ka event that is a global event affecting climate in both hemispheres (see below "The 8.2 ka event"). On a bigger scale, the hydroclimate variability in northwestern Madagascar potentially supports the latitudinal migration of the ITCZ, influencing the length of its visit in either hemisphere during the migration (Chiang & Bitz, 2005; Broccoli *et al*., 2006), that could be in or out of phase with the expansion or contraction of the rain belt (Yan *et al*., 2015; Denniston *et al*., 2016).

The Holocene records from stalagmite ANJB-2 and ANJ94-5 suggest a distinct hydrologic regime that can strongly reflect monsoon and ITCZ dynamics (Voarintsoa *et al*., 2017c; Wang *et al*., 2019). Stalagmite ANJB-2, replicated by another stalagmite MAJ-5 from a nearby Anjokipoty Cave, revealed three distinct intervals that are marked by 1) $CaCO_3$ deposition between ca. 9.8 and 7.8 ka BP, which was assigned the "Malagasy early Holocene interval" or MEHI, 2) a long depositional hiatus between ca. 7.8 and 1.6 ka BP, the "Malagasy mid-Holocene interval" or MMHI, and 3) resumption of $CaCO_3$ deposition after ca. 1.6 ka BP, the "Malagasy late Holocene

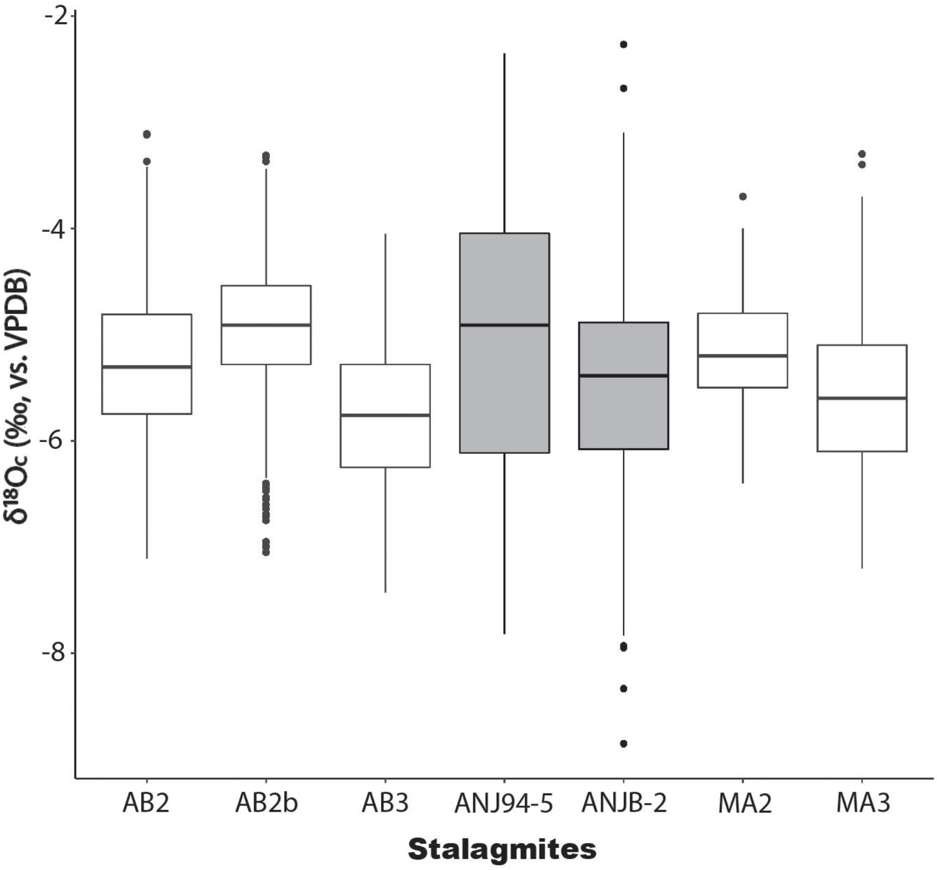

Figure 10. Box plot showing the range of $\delta^{18}O_c$ of the published stalagmites as of April-May 2020 from Anjohibe Cave. Indicated in grey are the two Holocene samples. Stalagmite AB2b is the same as AB2 but re-analyzed by Scroxton et al. (2017) at higher resolution.

interval" or MLHI. Each of these intervals of deposition records different isotopic signals (see Figure 4 of Voarintsoa *et al*., 2017c). A more complete record of the Holocene interval, as recorded by stalagmite ANJ94-5 (Wang *et al*., 2019), suggests six distinct climate periods, labelled Periods I to VI, with Period I similar to MEHI (generally recording wet conditions), Periods II to V corresponding to MMHI (with more complex climatology but generally drier conditions), and Period VI representing the early times of MLHI that also records anthropogenic changes to the surrounding landscape in northwestern Madagascar (Burns *et al*., 2016; Voarintsoa *et al*., 2017b, see also references therein).

Voarintsoa *et al*. (2017c) used the distinct intervals of stalagmite deposition (see their Figure 4) during the MEHI and the MLHI to infer that the cave was sufficiently supplied with water to allow stalagmites to grow during wetter conditions. Wang *et al*. (2019) additionally found that the early Holocene wet intervals coincide with part of the African Humid Period, AHP, a period marked by an intensification of the African monsoon due to earth orbital changes which increased summer season insolation forcing of the African monsoon (deMenocal *et al*., 2000). These wetter conditions potentially reflect a stronger monsoon. In contrast, the long-term depositional hiatus during the mid-Holocene was inferred as an interval of water shortage to the cave, which in turn could indicate a drier interval–as supported by additional proxies (petrography and mineralogy) from the same stalagmite (Voarintsoa *et al*., 2017c)–hence reflecting a weaker monsoon as a result of a northward migration of the ITCZ, agreeing with the model of Braconnot *et al*. (2007).

Early Holocene

Looking into more details of these Holocene speleothem records, for the period between 9.1 and 7.8 ka BP (called MEHI by Voarintsoa *et al*., 2017c and Period I by Wang *et al*., 2019), Voarintsoa *et al*. (2019) found a periodicity of ~800 years in the stalagmite ANJB-2 isotopic records (see their Figure 3) and an overall trend towards higher delta values towards the end of the MEHI, which ended with an abrupt depositional hiatus at ca. 7.8 ka BP. A periodogram performed on both stalagmite ANJ94-5 and stalagmite ANJB-2 $\delta^{18}O_c$ records, applying the Bartlett power spectrum using the Analyseries

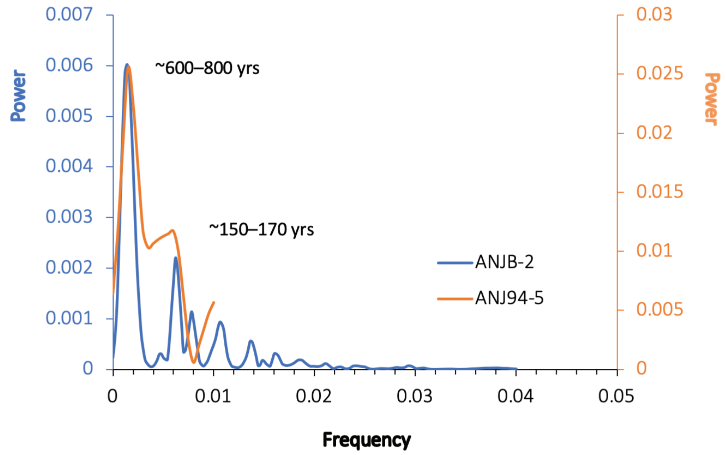

Figure 11. Periodogram of the MEHI and Period I from stalagmite ANJB-2 (Voarintsoa *et al*., 2017c) and stalagmite ANJ94-5 (Wang *et al*., 2019), respectively.

software 2.0.8 of Paillard *et al*. (1996), suggests a predominant periodicity of 600-800 years and another shorter periodicity of 150-170 years (Figure 11). The depositional hiatus terminating the MEHI is absent in stalagmite ANJ94-5, but at the early stage of Period II, a sharp increase (from ca. -7.0 to ca -2.5‰, vs. VPDB) in the speleothem $\delta^{18}O_c$ is evident around 7.3 ± 0.1 ka BP, which is additionally marked by the presence of aragonite (Wang *et al*., 2019), a mineral that is used as an indicator of dry conditions in speleothems (Murray, 1954; Thrailkill, 1971; Cabrol & Coudray, 1982; Railsback *et al*., 1994; Frisia *et al*., 2002). The 600-800-year periodicity could reflect the sub-millennial dynamics of the ITCZ (Fleitmann *et al*., 2004b) that migrated gradually and fairly continuously between the two hemispheres. The monsoonal responses to this migration could have influenced the isotopic signals reflecting the moisture source during its visits in the early Holocene. Such climatic conditions could have left northwestern Madagascar under the Tropical Savanna (Aw) climate, as it is today. It is also worth mentioning that the wet early Holocene period recorded in Madagascar ended sooner than the African Humid period (deMenocal *et al*., 2000), potentially suggesting an early northward shift of the ITCZ.

The 8.2 ka event

The most striking aspect of the Holocene speleothem records from Anjohibe Cave during the early Holocene interval is the preservation of the 8.2 ka event (Voarintsoa *et al*., 2019). The 8.2 ka event is classified as a "Glacial Aftermath" Rapid Climate Change of the early Holocene by Mayewski *et al*. (2004). It is defined as a clear abrupt climate perturbation of the early Holocene period (Alley *et al*., 1997; Barber *et al*., 1999) that was marked by regional cooling in the North Atlantic and surrounding regions (Alley *et al*., 1997; Klitgaard-Kristensen *et al*., 1998; Barber *et al*., 1999; Alley & Agustsdottir, 2005). This abrupt climate perturbation altered the density and salinity of the North Atlantic Deep Water (Thornalley *et al*., 2009), weakening the AMOC (Clark *et al*., 2001; Renssen *et al*., 2001; Dong & Sutton, 2002; Vellinga & Wood, 2002; Zhang & Delworth, 2005), leading to widespread cooling in the northern hemisphere regions (Clark *et al*., 2001; Thomas *et al*., 2007) but warming in the southern hemisphere regions (Wiersma *et al*., 2006).

In stalagmite ANJ94-5, the 8.2 ka is marked by a Type E surface, an erosional surface according to the petrographic classification of Railsback *et al*. (2013), created by undersaturated drip water during increased and more intense rainfall, removing approximately 260 years of deposited carbonate from 8.2 to 8.5 ka BP. In stalagmite ANJB-2, the 8.2 ka event is marked by two pulses of more negative isotopic values (Voarintsoa *et al*., 2019). The more negative values suggest an overall wetter period, a primary result of a southward migration of the ITCZ according to the model of Matero *et al*. (2017) that was used in the data-model comparison in Voarintsoa *et al*. (2019). The model simulation of Matero *et al*. (2017) produced a cooling pattern that is in good agreement with the amplitude and duration recorded in most of the robust European lake and North Atlantic sediment records (Morrill *et al*., 2013). The cold conditions led to southward pushing of the ITCZ, resulting in wetter conditions in northwestern Madagascar (Voarintsoa *et al*., 2019).

Assuming that the freshwater perturbations in the AMOC during the 8.2 ka event could also have altered the moisture sources' $\delta^{18}O$ values, stalagmites $\delta^{18}O_c$ in Anjohibe Cave can be expected to capture these changes with the more negative values (Voarintsoa *et al*., 2019). Stalagmites from Spain also record the 8.2 ka event (Dominguez-Villar *et al*., 2009).

The mid-Holocene

In contrast to the MEHI, the mid-Holocene interval in northwestern Madagascar (MMHI and Periods II-V in Voarintsoa *et al*., 2017c and Wang *et al*., 2019, ca. 7.8-1.6 ka BP) is much drier with a more dramatic climatic regime punctuated by several drought intervals lasting ca 100-300 years each (Wang *et al*., 2019). In stalagmite ANJB-2, there is clearly no carbonate deposited, suggesting a shortage in drip water feeding the speleothem (Voarintsoa *et al*., 2017c). In stalagmite ANJ94-5, Period II is marked by a series of much drier intervals that are associated with the deposition of aragonite and bounded by Type L surfaces, a boundary layer marking the progressive lessening of carbonate deposition according to the petrographic classification of Railsback *et al*. (2013), which also results from a shortage in the feeding drip water. Some intervals of carbonate deposition during the mid-Holocene are additionally interrupted by depositional hiatuses of about 830 years at ca. 6.81-5.98 ka BP, and of about 200 years at 4.2- 4 ka BP as a result of the drying conditions (Wang *et al.*, 2019).

Voarintsoa *et al*. (2017c) interpreted the extended depositional hiatus in stalagmite ANJB-2, and also in MAJ-5 from the nearby Anjokipoty Cave, to record an interval of northward migration of the ITCZ, starting at the end of the MEHI and potentially at the beginning of Period II (for the ANJ94-5 records). As noted above, the northward migration of the ITCZ in Madagascar began earlier than the ending of the wet AHP, and, hence, the ITCZ may have left Madagascar around the end of the MEHI. This northward migration, which may reflect longer or more intense summer seasons in the northern hemisphere, could suggest that the southernmost boundary of the ITCZ may have barely touched part of northwestern Madagascar, leading to a weakening of the Malagasy monsoon. It could also mean that summer seasons in the northwest became shorter, and, hence, rainfall amounts are significantly reduced to sufficiently supply water to Anjohibe Cave, and only a few stalagmites, such as the rare stalagmite ANJ94-5, can continue to grow with the remaining water stored in the epikarst and from small rainfall recharge.

Wang *et al*. (2019) specifically assigned several of the drought intervals during the mid-Holocene (at ca. 5.4 ka, 5.2 ka, and from 4.3 ka to 4.0 ka) to express global Rapid Climate Change (RCC) at 5.2 ka and 4.2 ka BP. The term RCC was used by Mayewski *et al*. (2004) to represent intervals of 'non-geographically nor temporally restrictive climate change', i.e. different from one's perception of the duration and magnitude of the last glacial periods, but to represent fast changes relative to human civilization. Both the 5.2 and the 4.2 ka events were assigned by Wang *et al*. (2019) as a dry period, which reflect the classic "cool poles, dry tropics" RCC of Mayewski *et al*. (2004). The causes and mechanisms behind these cool poles–dry tropics intervals are still poorly understood.

The late Holocene

The late Holocene interval is the most complicated amongst the intervals of the Holocene described earlier in Madagascar, as it coincides with times with more evidence of human colonization of the island and the megafaunal extinction (Burney & MacPhee, 1988; Burney, 1997; Dewar & Richard, 2012; Godfrey *et al*., 2019). This led recent researchers to investigate closely the differences between pristine vs. anthropogenic induced landscapes by looking at speleothem $\delta^{13}C_c$ (Burns *et al*., 2016; Voarintsoa *et al*., 2017b), sediment core proxies (Matsumoto & Burney, 1994), $\delta^{15}N$ values from radiocarbon-dated subfossil vertebrates (Crowley, 2010; Crowley & Samonds, 2013), and archaeological evidence (Wright *et al*., 1996; Crowther *et al*., 2016). Combining stable isotopes and petrographic features in stalagmite MA3, Voarintsoa *et al*. (2017b) inferred an interval of "favorable conditions" between 795 CE and 870 CE (see their Figure 8), which was interpreted as an interval of potentially prosperous lands under wetter climate, that could have attracted foragers (Wright *et al*., 1996; Beaujard, 2011) and maritime traders (Crowther *et al*., 2016) to settle in the island.

As a whole, the late Holocene stalagmite $\delta^{18}O_c$ records from Anjohibe Cave show a small amplitude of variability, except the relatively lower values between 800 and 1400 CE, if not considering the few peaks of drier conditions (Figure 12). In general, this small variability can suggest a relatively stable hydroclimate, hence monsoonal activities, in northwestern Madagascar, as noted by Voarintsoa *et al*. (2017b) and Scroxton *et al*. (2017). With higher resolution records, Scroxton *et al*. (2017) found

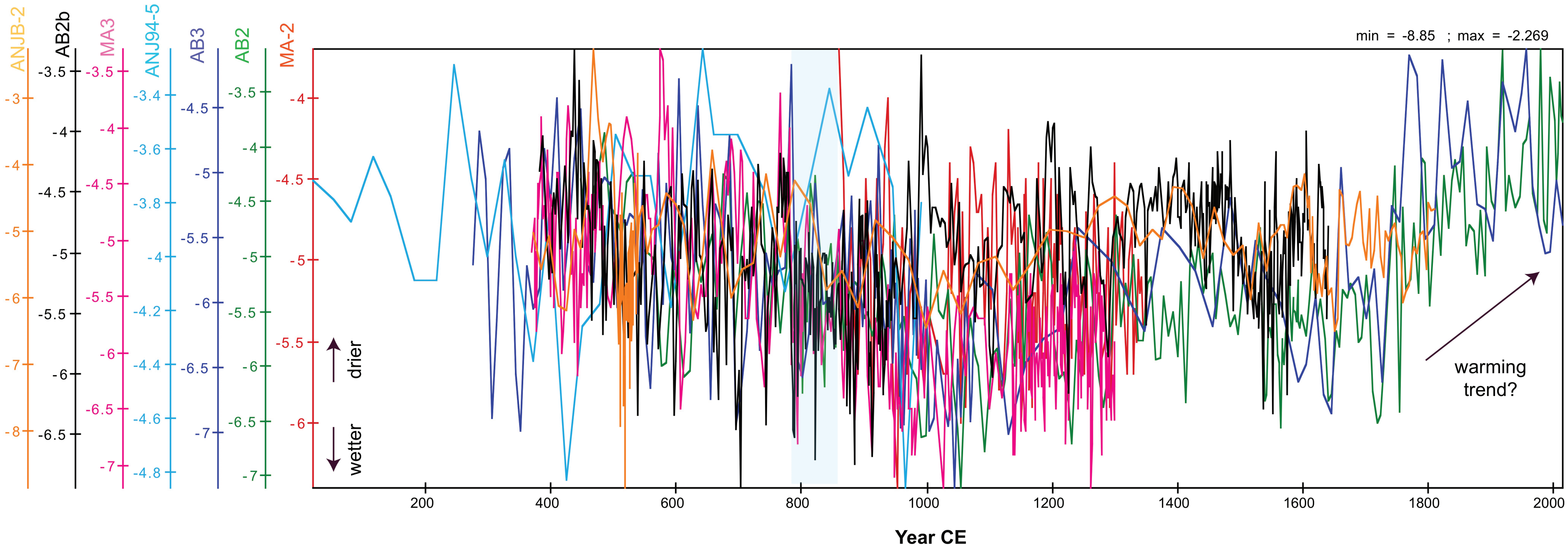

Figure 12. Late Holocene time series of all available speleothem $\delta^{18}O_c$ data from Anjohibe Cave as of April-May 2020. Highlighted in cyan is the interval of "favorable condition" discussed in Voarintsoa *et al.* (2017b) when climate conditions favored migrants to settle on Madagascar. The increased trend after ca. 1750-year CE could be evidence of a warming trend. Stalagmite AB2b is the same as AB2 but re-analyzed by Scroxton et al. (2017) at higher resolution.

a dominant $\delta^{18}O_c$ decadal scale variability with a range of 3.4‰ in stalagmite AB2. The causes of this decadal scale are yet to be investigated, given the precision of the age model per the authors' note, which may require additional speleothem samples preserving good laminations to refine the U-Th chronology. In general, Scroxton *et al*. (2017) assigned the variability in their records, following a speleothem $\delta^{18}O_c$ data comparison with Cave Defore, Oman (Burns *et al*., 2002), mainly to reflect the expansion and contraction of the ITCZ (Yan *et al*., 2015; Denniston *et al*., 2016). On the other hand, Voarintsoa *et al*. (2017b) found a semi-centennial cycle in the speleothem MA3 $\delta^{18}O_c$ records (average 50 years), dated before ~870 CE and no obvious cyclicity after then. This semi-centennial cycle was inferred to reflect an alternating wet/dry interval, as a result of a changing length of visit of the ITCZ in northwestern Madagascar in response to changing climate in regions of the Northern Hemisphere (exemplified by the changing temperature records in Europe; Büntgen *et al*., 2011), i.e., with more rainfall during longer visits (thus more negative $\delta^{18}O_c$), and with less rainfall during shorter visits (see Figure 8 of Voarintsoa *et al*., 2017b). In contrast, the absence of this semi-centennial cycle after ~870 CE in the same stalagmite MA3 records could simply suggest no significant shift of the ITCZ.

It is worth noting that the latitudinal migration of the ITCZ or its contraction/expansion could either be expected to influence monsoon hydroclimate in Madagascar, as discussed by Scroxton *et al*. (2017) and Voarintsoa *et al*. (2017b). The ITCZ brings either austral or boreal summer rainfall in either hemisphere. The overall lower $\delta^{18}O_c$ values between 800 and 1400 CE in the records may, in fact, reflect wetter conditions when the ITCZ moves relatively south, and potentially an enhanced summer season.

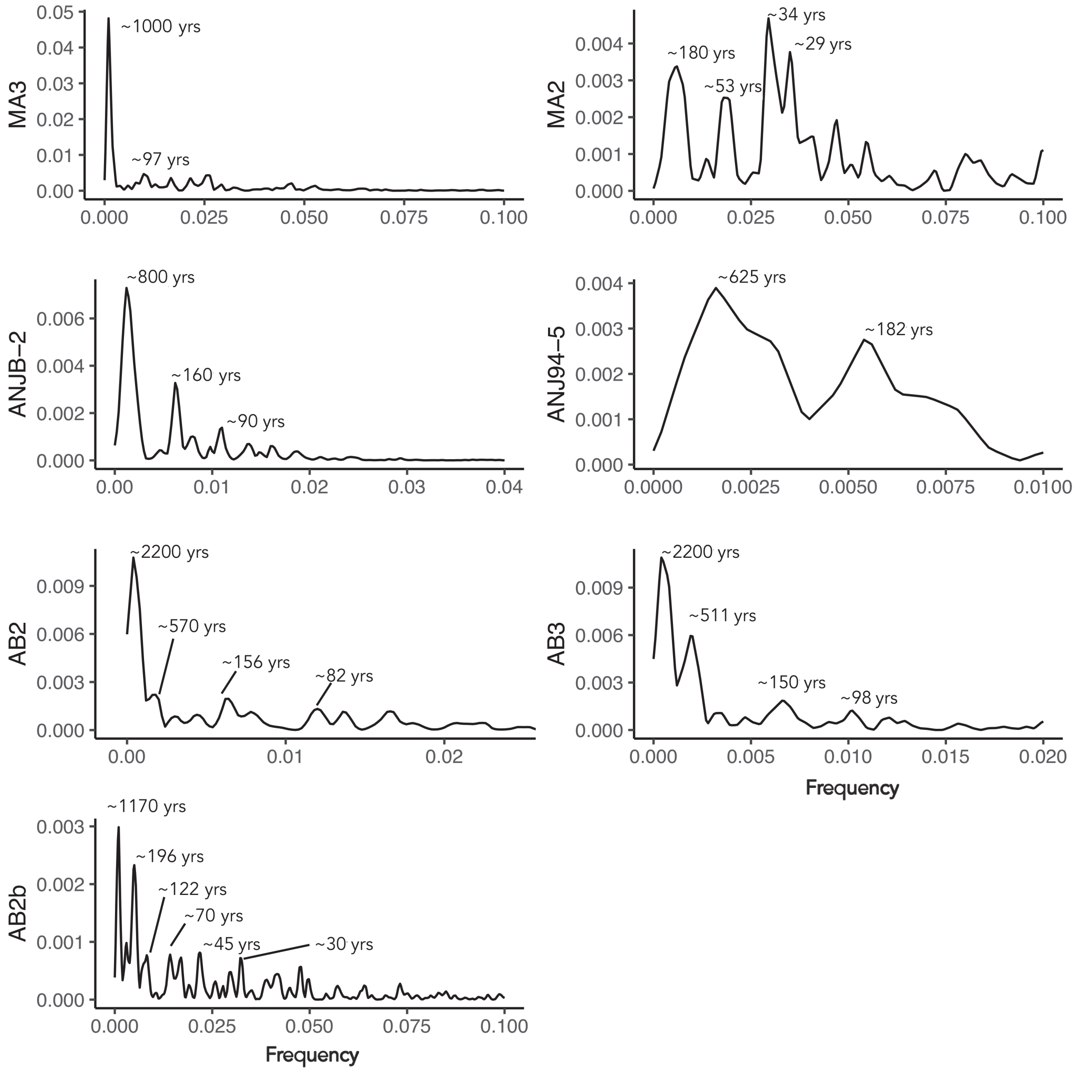

Figure 13. Periodogram runs on all available speleothem $\delta^{18}O_c$ from Anjohibe Cave as of April-May 2020. Note that AB2b is the same stalagmite as AB2, but b differentiates the high (Scroxton *et al*., 2017) vs. low resolution records (Burns *et al*., 2016).

With all the records of $\delta^{18}O_c$ compared, a series of periodograms performed on all speleothem records using Analyseries 2.0.8 reveals more frequencies (Figure 13). With the exception of the decadal periodicities, the most common are the sub-millennial periodicity (~800-1000 years), the sub-centennial periodicity (~100-200 years), and the multidecadal periodicity (~30-50 years), each potentially reflecting monsoonal changes, but with varying forcing mechanisms, e.g., interhemispheric difference in temperature leading to the latitudinal migration of the ITCZ (Chiang & Friedman, 2012) and potentially influencing the monsoon circulation in the Indian Ocean (Schott & McCreary, 2001); insolation (Kutzbach & Liu, 1997; Partridge *et al*., 1997); changes in sea surface temperature that may be linked to the Indian Ocean Dipole (Saji *et al*., 1999; Zheng *et al*., 2013); or changes in the Walker circulation that may have caused the contraction and expansion of the ITCZ over the western Indian Ocean.

From a closer observation of the late Holocene speleothem $\delta^{18}O_c$ records in Figure 12, an overall trend towards higher values is also observed starting after ca. 1750 CE, which surprisingly matches with the timing of another increasing speleothem $\delta^{18}O_c$ record in Dante Cave, Namibia, another region in the SH that is also influenced by the ITCZ (Voarintsoa *et al*., 2017a). While referring to the interhemispheric difference in temperature, as shown in the observed and simulated data from Neukom *et al*. (2014), the $\delta^{18}O_c$ trend observed in Dante Cave stalagmite has been ascribed to reflect more northward migration of the ITCZ, when the NH is warmer. The records from Madagascar could also reflect such migration and a weakening of the Malagasy monsoon. This could possibly explain the early cessation of some speleothem growth, such as stalagmites MA-2, MA-3, and ANJ94-5 (Figure 8).

The increasing isotopic trend observed in Namibia and Madagascar has a practical significance in their implications for future changes in rainfall, not only in northeastern Namibia but also in northwestern Madagascar. Warming of climate in the coming century is predicted for Earth in general and especially for high-latitude regions of the NH (IPCC, 2013). The correlation of past dry periods in northwestern Madagascar with this northward shift of the ITCZ toward a warmed NH, suggests that climate in the Mahajanga region could become drier if this northward migration of the ITCZ continues for the next century.

Challenges in proxy interpretation and future directions

To reconstruct the past climate and environmental changes in a region, two fundamental aspects need to be considered: 1) calibrating proxies from recently deposited speleothems with instrumental records, and 2) establishing a chronology with greater quantification of age uncertainty.

Proxy calibration can be an exciting approach for quantitative paleoclimate reconstruction, particularly in reconstructing past temperature and past rainfall. The strategic position of Madagascar relative to the latitudinal extent of the ITCZ, and the associated monsoonal responses, suggest the importance of oxygen isotope signals as proxies for rainfall amount. The challenges rest on the lack of long-term monitoring linking rainfall $\delta^{18}O_c$ and drip water $\delta^{18}O_{c.}$ The information from such investigations could subsequently help us better understand how geochemical signals are recorded in speleothems, and how these signals link to climate (van Breukelen *et al*., 2008). The global challenge in the calibration of speleothem $\delta^{18}O_c$ with modern rainfall to estimate paleorainfall is that the speleothem $\delta^{18}O_c$ and rainfall $\delta^{18}O_w$ relationship may not be constant over time (Lachniet, 2009). In addition, modern calibration is based on monthly averages, as long-term annual records of rainfall $\delta^{18}O_c$ are lacking from most locations, leaving a gap in fully extrapolating short term monitoring data to interpret longer-term paleorecords. Given the remote location of Anjohibe Cave, the accessibility to it becomes even more problematic during extremely rainy summer seasons. The practicability of long-term monitoring in the cave is not always easy. Nonetheless, a very fundamental approach in proxy calibration has been recently initiated in Anjohibe Cave, measuring the modern carbonate precipitates $\delta^{18}O_c$, the drip water $\delta^{18}O_{w,}$ and the drip water temperature (Voarintsoa *et al*., 2020a). This approach shows a general consistency of the isotopic fractionation factors vs. temperature with the global dataset. This implies the significant influence of in-cave temperature on speleothem $\delta^{18}O_c$ regardless of other factors that may also influence the variability of $\delta^{18}O_c$. As noted earlier, although the other potential controls on the kinetic isotope fractionation in Anjohibe Cave are not fully understood relative to cave locations elsewhere, this general consistency could be an important key to moving forward in using speleothem records as paleoclimate proxies. It could be combined with other proxies for reconstructing temperature (clumped isotopes, Δ_{47}; Kluge *et al*., 2013) and for reconstructing past relative humidity, which could strongly shed light on the notion of moisture sources (triple oxygen isotopes, $\Delta^{17}O$ or $^{17}O_{excess}$; Sha *et al*., 2020; Voarintsoa *et al*., 2020b). This could in turn provide a more complete picture of the drivers of the oxygen isotope variability in speleothems.

As mentioned earlier, our understanding of past climate changes mainly depends on linking together paleoclimate records from several locations worldwide to test and evaluate climate models. This may additionally require high temporal resolution records (annual to sub-annual) to resolve speleothem characteristics during a specific time interval (e.g., the past two millennia, the Little Ice Age or the Medieval Warm Period, the interval with greater anthropogenic changes) to gain a fuller picture of global climate change. Stalagmites with greater temporal uncertainty may become problematic when cross-comparing short-term paleoclimate records, a common problem for recently deposited stalagmites with higher detrital thorium. Limited accuracy in paleoclimate chronologies could also introduce uncertainty in paleoclimate reconstruction and linking paleoclimate records from different locations. Efforts have been made to minimize age uncertainties related to laboratory analyses when measuring ^{234}U and ^{230}Th on Faraday cups (Cheng *et al*., 2013). Others have used the relationship between $^{230}Th/^{232}Th$ values and ^{232}Th concentrations from the topmost layers of a stalagmite to correct the age with a unique $^{230}Th/^{232}Th$ value (Ridley *et al*., 2015). Strong knowledge of the sample's petrography has also become powerful to refine the U-Th based chronology (Railsback *et al*., 2013) as petrographic features in speleothems can represent a significant hiatus in the age model, hence minimizing the errors from building an age model.

Conclusion

Approaches to using speleothem $\delta^{18}O_c$ as a common proxy to reconstruct worldwide climate information have significantly grown over the past few decades, although their applications are relatively recent when considering the case of Madagascar. Oxygen isotopes are almost everywhere in the earth system (such as in the atmosphere, in water, in living organisms, and in rock-forming minerals), but each reservoir may be controlled by a myriad of factors. This paper has reviewed the usefulness of secondary limestone cave deposit oxygen isotope composition to understand paleoclimate, mainly the dynamics of ITCZ and monsoonal variations in Madagascar.

Since the monsoon in Madagascar is synchronized with the seasonal migration of the ITCZ, the ITCZ-monsoon relationship was simplified as follows: when the ITCZ moves further north, the Malagasy monsoon becomes weak, and when it is pushed further south, the Malagasy monsoon is strong (Voarintsoa *et al*., 2017b, 2017c, 2019). This latitudinal migration can be synchronous with an expansion or contraction of the tropical rain belt, potentially leading to unexpected phasing between the two hemispheres' tropical climate (Scroxton *et al*., 2017). Combining the modern speleothem $\delta^{18}O_c$-temperature calibration (see above) with the widely agreed "amount effect" influence on tropical rainfall $\delta^{18}O_w$, the periodicity and other significant climatic events (e.g., the 8.2 ka and other RCC events; Voarintsoa *et al*., 2019; Wang *et al*., 2019) revealed from stalagmites from Anjohibe Cave suggests that negative speleothem $\delta^{18}O_c$ values are indicative of stronger monsoon, whereas positive speleothem $\delta^{18}O_c$ values are indicative of weaker monsoon, and, hence, drier condition. The latter is further supported by the increasing trend toward more positive values (Figure 10) that coincides with the global warming trend, as reported in Namibia (Voarintsoa *et al*., 2017a). Despite uncertainties in the calibrations and chronology (see above), speleothem $\delta^{18}O_c$ time series from Anjohibe Cave have shed light on the linkage between terrestrial archives and atmospheric/oceanic climate dynamics, for example the dynamics of the thermohaline circulation during the 8.2 ka event. Speleothems have demonstrated a powerful ability to provide a meaningful sense of climatic change in the past, and with other geological archives from other locations worldwide, they can elucidate climate teleconnections between widely separated regions, with mindfulness to age model uncertainty and limitations to proxy calibrations.

Acknowledgments

The author would like to thank David Burney for the invitation to contribute to this special issue of *Malagasy Nature*. Nick Scroxton is also thanked for his detailed comments on an earlier version of the manuscript. Voarintsoa was supported by the EU-HORIZON Marie SkŁodowska Curie Fellowship H2020-MSCA-IF-2017 no. 796707. Some of the data presented in Figures 6 and 9 herein are funded by this grant.

References

Alley, R. B. 2000. The Younger Dryas cold interval as viewed from central Greenland. *Quaternary Science Reviews*, 19: 213-226.

Alley, R. B. & Agustsdottir, A. M. 2005. The 8 k event: Cause and consequences of a major Holocene abrupt climate change. *Quaternary Science Reviews*, 24: 1123-1149.

Alley, R. B., Mayewski, P. A., Sowers, T., Stuiver, M., Taylor, K. C. & Clark, P. U. 1997. Holocene climatic instability: A prominent, widespread event 8200 yr ago. *Geology*, 25: 483-486.

Arbuszewski, J. A., deMenocal, P. B., Cléroux, C., Bradtmiller, L. & Mix, A. 2013. Meridional shifts of the Atlantic intertropical convergence zone since the Last Glacial Maximum. *Nature Geoscience*, 6: 959-962.

Bar-Matthews, M., Ayalon, A., Matthews, A., Sass, E. & Halicz, L. 1996. Carbon and oxygen isotope study of the active water-carbonate system in a karstic Mediterranean cave: Implications for paleoclimate research in semiarid regions. *Geochimica et Cosmochimica Acta*, 60: 337-347.

Barber, D. C., Dyke, A., Hillaire-Marcel, C., Jennings, A. E., Andrews, J. T., Kerwin, M. W., Bilodeau, G., McNeely, R., Southon, J., Morehead, M. D. & Gagnon, J. M. 1999. Forcing of the cold event of 8,200 years ago by catastrophic drainage of Laurentide lakes. *Nature*, 400: 344-348.

Barrett, M. A., Brown, J. L., Junge, R. E. & Yoder, A. D. 2013. Climate change, predictive modeling and lemur health: Assessing impacts of changing climate on health and conservation in Madagascar. *Biological Conservation*, 157: 409-422.

Basha, G., Kishore, P., Venkat Ratnam, M., Ouarda, T. B. M. J., Velicogna, I. & Sutterley, T. 2015. Vertical and latitudinal variation of the intertropical convergence zone derived using GPS radio occultation measurements. *Remote Sensing of Environment*, 163: 262-269.

Beaujard, P. 2011. The first migrants to Madagascar and their introduction of plants: Linguistic and ethnological evidence. *Azania*, 46: 169-189.

Benson, C. & Clay, E. 1998. The impact of droughts on sub-Saharan African economies. *World Bank Technical Paper*, 401: 80.

Berger, A. 2009. Monsoon and general circulation system. *Chinese Science Bulletin*, 54: 1111-1112.

Black, D. E. 2002. The rains may be a-comin'. *Science*, 297: 528-529.

Black, E., Slingo, J. & Sperber, K. R. 2003. An observational study of the relationship between excessively strong short rains in coastal East Africa and Indian Ocean SST. *Monthly Weather Review*, 131: 74-94.

Boch, R., Spötl, C. & Kramers, J. 2009. High-resolution isotope records of early Holocene rapid climate change from two coeval stalagmites of Katerloch Cave, Austria. *Quaternary Science Reviews*, 28: 2527-2538.

Bowen, G. J. 2020. The Online Isotopes in Precipitation Calculator, version 3.1 http://www.waterisotopes.org. Accessed May 24, 2020

Bowen, G. J. & Revenaugh, J. 2003. Interpolating the isotopic composition of modern meteoric precipitation. *Water Resources Research*, 39 (10). https://doi.org/10.1029/2003WR002086

Bowen, G. J. & Wilkinson, B. 2002. Spatial distribution of $\delta^{18}O$ in meteoric precipitation. *Geology*, 30: 315-318.

Bowen, G. J., Wassenaar, L. I. & Hobson, K. A. 2005. Global application of stable hydrogen and oxygen isotopes to wildlife forensics. *Oecologia*, 143: 337-348.

Braconnot, P., Otto-Bliesner, B., Harrison, S., Joussaume, S., Peterchmitt, J.-Y., Abe-Ouchi, A., Crucifix, M., Driesschaert, E., Fichefet, T., Hewitt, C. D., Kageyama, M., Kitoh, A., Laîné, A., Loutre, M.-F., Marti, O., Merkel, U., Ramstein, G., Valdes, P., Weber, S. L., Yu, Y. & Zhao, Y. 2007. Results of PMIP2 coupled simulations of the Mid-Holocene and Last Glacial Maximum – Part 1: Experiments and large-scale features. *Climate of the Past*, 3: 261-277.

Broccoli, A. J., Dahl, K. A. & Stouffer, R. J. 2006. Response of the ITCZ to Northern Hemisphere cooling. *Geophysical Research Letters*, 33.

Broecker, W. S. 1991. The great ocean conveyor. *Oceanography*, 4: 79-89.

Bruggemann, J. H., Rodier, M., Guillaume, M. M. M., Andrefouet, S., Arfi, R., Cinner, J. E., Pichon, M., Ramahatratra, F., Rasoamanendrika, F., Zinke, J. & McClanahan, T. R. 2012. Wicked social-ecological problems forcing unprecedented change on the latitudinal margins of coral reefs: The case of southwest Madagascar. *Ecology and Society*, 17.

Büntgen, U., Tegel, W., Nicolussi, K., McCormick, M., Frank, D., Trouet, V., Kaplan, J. O., Herzig, F., Heussner, K. U., Wanner, H., Luterbacher, J. & Esper, J. 2011. 2500 years of European climate variability and human susceptibility. *Science*, 331: 578-582.

Burney, D. 1997. Theories and facts regarding Holocene environmental change before and after human colonization. In *Natural change and human impact in Madagascar*, eds. S. M. Goodman & B. D. Patterson, pp. 75-89. Smithsonian Institution Press, Washington, D.C.

Burney, D. A. & MacPhee, R. D. E. 1988. Mysterious island: What killed Madagascar's large native animals? *Natural History Magazine*, 97: 46-55.

Burns, S. J., Fleitmann, D., Mudelsee, M., Neff, U., Matter, A. & Mangini, A. 2002. A 780-year annually resolved record of Indian Ocean monsoon precipitation from a speleothem from south Oman. *Journal of Geophysical Research-Atmospheres*, 107 (D20): ACL 9-1-ACL 9-9.

Burns, S. J., Godfrey, L. R., Faina, P., McGee, D., Hardt, B., Ranivoharimanana, L. & Randrianasy, J. 2016. Rapid human-induced landscape transformation in Madagascar at the end of the first millennium of the Common Era. *Quaternary Science Reviews*, 134: 92-99.

Cabrol, P. & Coudray, J. 1982. Climatic fluctuations influence the genesis and diagenesis of carbonate speleothems in southwestern France. *National Speleological Society Bulletin*, 44: 112-117.

Cacho, I., Grimalt, J. O., Pelejero, C., Canals, M., Sierro, F. J., Flores, J. A. & Shackleton, N. 1999. Dansgaard-Oeschger and Heinrich event imprints in Alboran Sea paleotemperatures. *Paleoceanography*, 14: 698-705.

Cane, M. A., Eshel, G. & Buckland, R. W. 1994. Forecasting Zimbabwean maize yield using eastern equatorial Pacific sea-surface temperature. *Nature*, 370: 204-205.

Cheng, H., Edwards, R. L., Shen, C. C., Polyak, V. J., Asmerom, Y., Woodhead, J., Hellstrom, J., Wang, Y. J., Kong, X. G., Spötl, C., Wang, X. F. & Alexander, E. C. 2013. Improvements in ^{230}Th dating, ^{230}Th and ^{234}U half-life values, and U-Th isotopic measurements by multi-collector inductively coupled plasma mass spectrometry. *Earth and Planetary Science Letters*, 371: 82-91.

Chiang, J. C. H. & Bitz, C. M. 2005. Influence of high latitude ice cover on the marine Intertropical Convergence Zone. *Climate Dynamics*, 25: 477-496.

Chiang, J. C. H. & Friedman, A. R. 2012. Extratropical cooling, interhemispheric thermal gradients, and tropical climate change. *Annual Review of Earth and Planetary Sciences*, 40: 383-412

Clark, P. U., Marshall, S. J., Clarke, G. K. C., Hostetler, S. W., Licciardi, J. M. & Teller, J. T. 2001. Freshwater forcing of abrupt climate change during the last glaciation. *Science*, 293: 283-287.

Comas-Bru, L., Harrison, S. P., Werner, M., Rehfeld, K., Scroxton, N., Veiga-Pires, C. & SISAL working group members. 2019. Evaluating model outputs using integrated global speleothem records of climate change since the last glacial. *Climates of the Past*, 15: 1557-1579.

Crowley, B. E. 2010. A refined chronology of prehistoric Madagascar and the demise of the megafauna. *Quaternary Science Reviews*, 29: 2591-2603.

Crowley, B. E. & Samonds, K. E. 2013. Stable carbon isotope values confirm a recent increase in grasslands in northwestern Madagascar. *The Holocene*, 23: 1066-1073.

Crowther, A., Lucas, L., Helm, R., Horton, M., Shipton, C., Wright, H. T., Walshaw, S., Pawlowicz, M., Radimilahy, C., Douka, K., Picornell-Gelabert, L., Fuller, D. Q. & Boivin, N. L. 2016. Ancient crops provide first archaeological signature of the westward Austronesian expansion. *Proceedings of the National Academy of Sciences of the USA*, 113: 6635-6640.

Cruz, F., Burns, S., Jercinovic, M., Karmann, I., Sharp, W. & Vuille, M. 2007. Evidence of rainfall variations in Southern Brazil from trace element ratios (Mg/Ca and Sr/ Ca) in a Late Pleistocene stalagmite. *Geochimica et Cosmochimica Acta*, 71: 2250-2263.

Daëron, M., Drysdale, R. N., Peral, M., Huyghe, D., Blamart, D., Coplen, T. B., Lartaud, F. & Zanchetta, G. 2019. Most Earth-surface calcites precipitate out of isotopic equilibrium. *Nature Communications*, 10: 1-7.

Dansgaard, W. 1964. Stable isotopes in precipitation. *Tellus*, 16: 436-468.

Day, C. & Henderson, G. 2011. Oxygen isotopes in calcite grown under cave-analogue conditions. *Geochimica et Cosmochimica Acta*, 75: 3956-3972.

deMenocal, P., Ortiz, J., Guilderson, T., Adkins, J., Sarnthein, M., Baker, L. & Yarusinsky, M. 2000. Abrupt onset and termination of the African Humid Period: Rapid climate responses to gradual insolation forcing. *Quaternary Science Reviews*, 19: 347-361.

Denniston, R. F., Ummenhofer, C. C., Wanamaker, A. D., Lachniet, M. S., Villarini, G., Asmerom, Y., Polyak, V. J., Passaro, K. J., Cugley, J., Woods, D. & Humphreys, W. F. 2016. Expansion and contraction of the Indo-Pacific Tropical Rain Belt over the last three millennia. *Scientific Reports*, 6: 34485.

Dewar, R. E. & Richard, A. F. 2012. Madagascar: A history of arrivals, what happened, and will happen next. *Annual Review of Anthropology*, 41: 495-517.

DGM. 2008. Le changement climatique à Madagascar. Direction Générale de la Météorologie, Antananarivo.

Dominguez-Villar, D., Fairchild, I. J., Baker, A., Wang, X. F., Edwards, R. L. & Cheng, H. 2009. Oxygen isotope precipitation anomaly in the North Atlantic region during the 8.2 ka event. *Geology*, 37: 1095-1098.

Dong, B. W. & Sutton, R. T. 2002. Adjustment of the coupled ocean-atmosphere system to a sudden change in the Thermohaline Circulation. *Geophysical Research Letters*, 29: 1728.

Donohoe, A., Atwood, A. R. & Byrne, M. P. 2019. Controls on the width of tropical precipitation and its contraction under global warming. *Geophysical Research Letters*, 46: 9958-9967.

Edwards, R. L., Chen, J. H. & Wasserburg, G. J. 1987. ^{238}U-^{234}U-^{230}Th-^{232}Th systematics and the precise measurement of time over the past 500,000 years, *Earth and Planetary Science Letters*, 81: 175-192.

Emiliani, C. 1966. Isotopic paleotemperatures. *Science*, 154: 851-857.

Fairchild, I. J. & Baker, A. 2012. Speleothem science: From processes to past environments. Wiley-Blackwell.

Fairchild, I. J. & McMillan, E. A. 2007. Speleothems as indicators of wet and dry periods. *International Journal of Speleology*, 36: 9-74.

Fleitmann, D., Burns, S. J., Neff, U., Mudelsee, M., Mangini, A. & Matter, A. 2004a. Palaeoclimatic interpretation of high-resolution oxygen isotope profiles derived from annually laminated speleothems from southern Oman. *Quaternary Science Reviews*, 23: 935-945.

Fleitmann, D., Burns, S. J., Neff, U., Mudelsee, M., Mangini, A., Kramers, J. & Matter, A. 2004b. Holocene records of rainfall variation and associated ITCZ migration from stalagmites from northern and southern Oman. In *The Hadley Circulation: Present,* *past and future*, eds. H. F. Diaz & R. S. Bradley, pp. 259-287. Springer, Dordrecht.

Frierson, D. M. W. & Hwang, Y. T. 2012. Extratropical influence on ITCZ shifts in slab ocean simulations of global warming. *Journal of Climate*, 25: 720-733.

Frisia, S., Borsato, A., Fairchild, I. J., McDermott, F. & Selmo, E. M. 2002. Aragonite-calcite relationships in speleothems (Grotte de Clamouse, France): Environment, fabrics, and carbonate geochemistry. *Journal of Sedimentary Research*, 772: 687-699.

Gadgil, S. 2003. The Indian monsoon and its variability. *Annual Review of Earth and Planetary Sciences*, 31: 429-467.

Godfrey, L. R., Scroxton, N., Crowley, B. E., Burns, S. J., Sutherland, M. R., Pérez, V. R., Faina, P., McGee, D. & Ranivoharimanana, L. 2019. A new interpretation of Madagascar's megafaunal decline: The "Subsistence Shift Hypothesis". *Journal of Human Evolution*, 130: 126-140.

Hansen, M., Scholz, D., Schöne, B. R. & Spötl, C. 2019. Simulating speleothem growth in the laboratory: Determination of the stable isotope fractionation ($\delta^{13}C$ and $\delta^{18}O$) between H_2O, DIC and $CaCO_3$. *Chemical Geology*, 509: 20-44.

Heath, T. 2010. *Madagascar climate change briefing*. Water & sanitation for the urban poor. Cranfield University, Bedford.

Hendy, C. H. & Wilson, A. T. 1968. Paleoclimatic data from speleothems. *Nature*, 219: 48-51.

Hill, C. & Forti, P. 1997. *Cave minerals of the World*. National Speleological Society, Huntsville.

Hondula, D. M., Rocklov, J. & Sankoh, O. A. 2012. Past, present, and future climate at select INDEPTH member Health and Demographic Surveillance Systems in Africa and Asia. *Global Health Action*, 5(1), 19083. DOI: 10.3402/gha.v5i0.19083

IAEA/WMO. 2004. Global network of isotopes in precipitation. The GNIP database. Available from http://isohis.iaea.org (Accessed 27 September 2013).

IPCC. 2013. Summary for policymakers. In *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds. T. F. Stocker, D. Qin, G. K. Plattner, M. M. B. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P. M. Midgley & Working Group I Technical Support Unit, pp. 3-32. Cambridge University Press, Cambridge.

Johnston, V., Borsato, A., Spötl, C., Frisia, S. & Miorandi, R. 2013. Stable isotopes in caves over altitudinal gradients: Fractionation behaviour and inferences for speleothem sensitivity to climate change. *Climate of the Past*, 9: 99.

Jury, M. R. 2003. The climate of Madagascar. In *The natural history of Madagascar*, eds. S. M. Goodman & J. P. Benstead, pp. 75-87. The University of Chicago Press, Chicago.

Kang, S. M., Held, I. M., Frierson, D. M. W. & Zhao, M. 2008. The response of the ITCZ to extratropical thermal forcing: Idealized slab-ocean experiments with a GCM. *Journal of Climate*, 21: 3521-3532.

Kim, S.-T. & O'Neil, J. R. 1997. Equilibrium and nonequilibrium oxygen isotope effects in synthetic carbonates. *Geochimica et Cosmochimica Acta*, 61: 3461-3475.

Klitgaard-Kristensen, D., Sejrup, H.-P., Haflidason, H., Johnsen, S. & Spurk, M. 1998. A regional 8200 cal. yr BP cooling event in northwest Europe, induced by final stages of the Laurentide ice-sheet deglaciation? *Journal of Quaternary Sciences*, 13: 165-169.

Kluge, T., Affek, H., Marx, T., Aeschbach-Hertig, W., Riechelmann, D., Scholz, D., Riechelmann, S., Immenhauser, A., Richter, D. & Fohlmeister, J. 2013. Reconstruction of drip-water $\delta^{18}O$ based on calcite oxygen and clumped isotopes of speleothems from Bunker Cave (Germany). *Climate of the Past*, 9: 377-391.

Kutzbach, J. E. & Liu, Z. 1997. Response of the African monsoon to orbital forcing and ocean feedbacks in the Middle Holocene. *Science*, 278: 440-443.

Lachniet, M. S. 2009. Climatic and environmental controls on speleothem oxygen-isotope values. *Quaternary Science Reviews*, 28: 412-432.

Leech, P. J., Lynch-Stieglitz, J. & Zhang, R. 2013. Western Pacific thermocline structure and the Pacific marine Intertropical Convergence Zone during the Last Glacial Maximum. *Earth and Planetary Science Letters*, 363: 133-143.

LeGrande, A. N. & Schmidt, G. A. 2006. Global gridded data set of the oxygen isotopic composition in seawater. *Geophysical Research Letters*, 33: L12604

Lynch-Stieglitz, J. 2017. The Atlantic meridional overturning circulation and abrupt climate change. *Annual Review of Marine Science*, 9: 83-104.

Matero, I. S. O., Gregoire, L. J., Ivanovic, R. F., Tindall, J. C. & Haywood, A. M. 2017. The 8.2 ka cooling event caused by Laurentide ice saddle collapse. *Earth and Planetary Science Letters*, 473: 205-214.

Matsumoto, K. & Burney, D. A. 1994. Late Holocene environments at Lake Mitsinjo, northwestern Madagascar. *The Holocene*, 4: 16-24.

Mayewski, P. A., Rohling, E. E., Stager, C. J ., Karlen, W., Maasch, K. A., Meeker, L. D., Meyerson, E. A., Gasse, F., van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R. R. & Steig, E. J. 2004. Holocene climate variability. *Quaternary Research*, 62: 243-255.

McDermott, F. 2004. Palaeo-climate reconstruction from stable isotope variations in speleothems: A review. *Quaternary Science Reviews*, 23: 901-918.

McDermott, F., Mattey, D. P. & Hawkesworth, C. 2001. Centennial-scale Holocene climate variability revealed by a high-resolution speleothem delta O-18 record from SW Ireland. *Science*, 294: 1328-1331.

McGee, D., Donohoe, A., Marshall, J. & Ferreira, D. 2014. Changes in ITCZ location and cross-equatorial heat transport at the Last Glacial Maximum, Heinrich

Stadial 1, and the mid-Holocene. *Earth and Planetary Science Letters*, 390: 69-79.

Mickler, P. J., Stern, L. A. & Banner, J. L. 2006. Large kinetic isotope effects in modern speleothems. *GSA Bulletin*, 118: 65-81.

Morrill, C., LeGrande, A. N., Renssen, H., Bakker, P. & Otto-Bliesner, B. L. 2013. Model sensitivity to North Atlantic freshwater forcing at 8.2 ka. *Climate of the Past*, 9: 955-968.

Murray, J. W. 1954. The deposition of calcite and aragonite in caves. *Journal of Geology*, 62: 481-492.

Neukom, R., Gergis, J., Karoly, D. J., Wanner, H., Curran, M., Elbert, J., Gonzalez-Rouco, F., Linsley, B. K., Moy, A. D., Mundo, I., Raible, C. C., Steig, E. J., van Ommen, T., Vance, T., Villalba, R., Zinke, J. & Frank, D. 2014. Inter-hemispheric temperature variability over the past millennium. *Nature Climate Change*, 4: 362-367.

Paillard, D., Labeyrie, L. & Yiou, P. 1996. Macintosh program performs time-series analysis. *Eos, Transactions American Geophysical Union*, 77: 379.

Partridge, T. C., DeMenocal, P. B., Lorentz, S. A., Paiker, M. J. & Vogel, J. C. 1997. Orbital forcing of climate over South Africa: A 200,000-year rainfall record from the Pretoria saltpan. *Quaternary Science Reviews*, 16: 1125-1133.

Poulson, T. L. & White, W. B. 1969. The cave environment. *Science*, 165: 971-981.

Railsback, L. B., Brook, G. A., Chen, J., Kalin, R. & Fleisher, C. J. 1994. Environmental controls on the petrology of a late Holocene speleothem from Botswana with annual layers of aragonite and calcite. *Journal of Sedimentary Research*, 64: 147-155.

Railsback, L. B., Akers, P. D., Wang, L., Holdridge, G. A. & Voarintsoa, N. R. G. 2013. Layer-bounding surfaces in stalagmites as keys to better paleoclimatological histories and chronologies. *International Journal of Speleology*, 42: 167-180.

Railsback, L. B., Brook, G. A., Liang, F., Voarintsoa, N. R. G., Cheng, H. & Edwards, R. L. 2018. A multi-proxy climate record from a northwestern Botswana stalagmite suggesting wetness late in the Little Ice Age (1810-1820 CE) and drying thereafter in response to changing migration of the tropical rain belt or ITCZ. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 506: 139-153.

Renssen, H., Goosse, H., Fichefet, T. & Campin, J.-M. 2001. The 8.2 kyr BP event simulated by a global atmosphere–sea-ice–ocean model. *Geophysical Research Letters*, 28: 1567-1570.

Ridley, H. E., Asmerom, Y., Baldini, J. U. L., Breitenbach, S. F. M., Aquino, V. V., Prufer, K. M., Culleton, B. J., Polyak, V., Lechleitner, F. a., Kennett, D. J., Zhang, M., Marwan, N., Macpherson, C. G., Baldini, L. M., Xiao, T., Peterkin, J. L., Awe, J. & Haug, G. H. 2015. Aerosol forcing of the position of the intertropical convergence zone since ad 1550. *Nature Geoscience*, 8: 195-200.

Risi, C., Bony, S. & Vimeux, F. 2008. Influence of convective processes on the isotopic composition ($\delta^{18}O$ and δD) of precipitation and water vapor in the tropics: 2. Physical interpretation of the amount effect. *Journal of Geophysical Research-Atmospheres*, 113 (D9). https://doi.org/10.1029/2008JD009943

Rubel, F. & Kottek, M. 2010. Observed and projected climate shifts 1901–2100 depicted by world maps of the Köppen-Geiger climate classification. *Meteorologische Zeitschrift*, 19: 135-141.

Saji, N. H., Goswami, B. N., Vinayachandran, P. N. & Yamagata, T. 1999. A dipole mode in the tropical Indian Ocean. *Nature*, 401: 360-363.

Sarr, B. 2012. Present and future climate change in the semi-arid region of West Africa: A crucial input for practical adaptation in agriculture. *Atmospheric Science Letters*, 13: 108-112.

Schott, F. A. & McCreary, J. P. 2001. The monsoon circulation of the Indian Ocean. *Progress in Oceanography*, 51: 1-123.

Scroxton, N., Burns, S. J., McGee, D., Hardt, B., Godfrey, L. R., Ranivoharimanana, L. & Faina, P. 2017. Hemispherically in-phase precipitation variability over the last 1700 years in a Madagascar speleothem record. *Quaternary Science Reviews*, 164: 25-36.

Sha, L., Mahata, S., Duan, P., Luz, B., Zhang, P., Baker, J., Zong, B., Ning, Y., Brahim, Y.A. & Zhang, H. 2020. A novel application of triple oxygen isotope ratios of speleothems. *Geochimica et Cosmochimica Acta*, 270: 360-378.

Sinha, A., Stott, L., Berkelhammer, M., Cheng, H., Edwards, R. L., Buckley, B., Aldenderfer, M. & Mudelsee, M. 2011. A global context for megadroughts in monsoon Asia during the past millennium. *Quaternary Science Reviews*, 30: 47-62.

Thomas, E. R., Wolff, E. W., Mulvaney, R., Steffensen, J. P., Johnsen, S. J., Arrowsmith, C., White, J. W. C., Vaughn, B. & Popp, T. 2007. The 8.2 ka event from Greenland ice cores. *Quaternary Science Reviews*, 26: 70-81.

Thompson, P., Schwarcz, H. P. & Ford, D. E. 1974. Continental Pleistocene climatic variation from speleothem age and isotopic data. *Science*, 184: 893-895.

Thornalley, D. J. R., Elderfield, H. & McCave, I. N. 2009. Holocene oscillations in temperature and salinity of the surface subpolar North Atlantic. *Nature*, 457: 711-714.

Thrailkill, J. 1971. Carbonate deposition in Carlsbad caverns. *Journal of Geology* 79: 683-695.

Thuiller, W., Midgley, G. F., Hughes, G. O., Bomhard, B., Drew, G., Rutherford, M. C. & Woodward, F. I. 2006. Endemic species and ecosystem sensitivity to climate change in Namibia. *Global Change Biology*, 12: 759-776.

Tremaine, D. M., Froelich, P. N. & Wang, Y. 2011. Speleothem calcite farmed in situ: Modern calibration of $\delta^{18}O$ and $\delta^{13}C$ paleoclimate proxies in a continuouslymonitored natural cave system. *Geochimica et Cosmochimica Acta*, 75: 4929-4950.

Trenberth, K. E., Stepaniak, D. P. & Caron, J. M. 2000. The global monsoon as seen through the divergent atmospheric circulation. *Journal of Climate*, 13: 3969-3993.

UNICEF. 2019. Improving access to safe water in southern Madagascar: Using scientific methodologies and satellite imagery to locate water resources. https://www.unicef.org/innovation/stories/improving-safe-water-access-madagascar. Accessed on 19 June 2020

Urey, H. C. 1947. The thermodynamic properties of isotopic substances. *Journal of the Chemical Society*, 562-581.

van Breukelen, M. R., Vonhof, H. B., Hellstrom, J. C., Wester, W. C. G. & Kroon, D. 2008. Fossil dripwater in stalagmites reveals Holocene temperature and rainfall variation in Amazonia. *Earth and Planetary Science Letters*, 275: 54-60.

Vellinga, M. & Wood, R. A. 2002. Global climatic impacts of a collapse of the Atlantic thermohaline circulation. *Climatic Change*, 54: 251-267.

Voarintsoa, N. R. G. 2017. Investigating stalagmites from NE Namibia and NW Madagascar as a key to better understand local paleoenvironmental changes and implications for inter-tropical convergence zone (ITCZ) dynamics. Ph.D. thesis, University of Georgia, Athens.

Voarintsoa, N. R. G., Brook, G. A., Liang, F. Y., Marais, E., Hardt, B., Cheng, H., Edwards, R. L. & Railsback, L. B. 2017a. Stalagmite multi-proxy evidence of wet and dry intervals in northeastern Namibia: Linkage to latitudinal shifts of the Inter-Tropical Convergence Zone and changing solar activity from AD 1400 to 1950. *The Holocene*, 27: 384-396.

Voarintsoa, N. R. G., Wang, L. X., Railsback, L. B., Brook, G. A., Liang, F. Y., Cheng, H. & Edwards, R. L. 2017b. Multiple proxy analyses of a U/Th-dated stalagmite to reconstruct paleoenvironmental changes in northwestern Madagascar between 370 CE and 1300 CE. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 469: 138-155.

Voarintsoa, N. R. G., Railsback, L. B., Brook, G. A., Wang, L., Kathayat, G., Cheng, H., Li, X., Edwards, R. L., Rakotondrazafy, A. F. M. & Madison Razanatseheno, M. O. 2017c. Three distinct Holocene intervals of stalagmite deposition and nondeposition revealed in NW Madagascar, and their paleoclimate implications. *Climate of the Past*, 13: 1771-1790.

Voarintsoa, N. R. G., Matero, I. S. O., Railsback, L. B., Gregoire, L. J., Tindall, J., Sime, L., Cheng, H., Edwards, R. L., Brook, G. A., Kathayat, G., Li, X., Rakotondrazafy, A. F. M. & Madison Razanatseheno, M. O. 2019. Investigating the 8.2 ka event in northwestern Madagascar: Insight from data-model comparisons. *Quaternary Science Reviews*, 204: 172-186.

Voarintsoa, N. R .G, Ratovonanahary, A. L. A., Rakotovao, Z. M. & Bouillon, S. 2020a. Understanding modern kinetic isotope effect in Anjohibe cave, in Northwestern Madagascar: A key to calibrate speleothem $\delta^{18}O$ and $\delta^{13}C$. EGU General Assembly. https://doi.org/10.5194/egusphere-egu2020-4855

Voarintsoa, N. R. G., Barkan, E., Bergel, S., Vieten, R. & Affek, H. P. 2020b. Triple oxygen isotope fractionation between $CaCO_3$ and H_2O in inorganically precipitated calcite and aragonite. *Chemical Geology*, 539: 119500.

Wang, B. & Ding, Q. H. 2008. Global monsoon: Dominant mode of annual variation in the tropics. *Dynamics of Atmospheres and Oceans,* 44: 165-183.

Wang, L., Brook, G. A., Burney, D. A., Voarintsoa, N. R. G., Liang, F., Cheng, H. & Edwards, R. L. 2019. The African Humid Period, rapid climate change events, the timing of human colonization, and megafaunal extinctions in Madagascar during the Holocene: Evidence from a 2 m Anjohibe Cave stalagmite. *Quaternary Science Reviews*, 210: 136-153.

Wang, P. X. 2009. Global monsoon in a geological perspective. *Chinese Science Bulletin*, 54: 1113-1136.

Wells, N. A. 2003. Some hypotheses on the Mesozoic and Cenozoic paleoenvironmental history of Madagascar. In *The natural history of Madagascar*, eds. S. M. Goodman & J. P. Benstead, pp. 16-34. The University of Chicago Press, Chicago.

Wiersma, A. P., Renssen, H., Goosse, H. & Fichefet, T. 2006. Evaluation of different freshwater forcing scenarios for the 8.2 ka BP event in a coupled climate model. *Climate Dynamics*, 27: 831-849.

Wong, C. I. & Breecker, D .O. 2015. Advancements in the use of speleothems as climate archives. *Quaternary Science Reviews*, 127: 1-18.

Wright, H. T., Vérin, P., Ramilisonina, Burney, D., Burney, L. P. & Matsumoto, K. 1996. The evolution of settlement systems in the Bay of Boeny and the Mahavavy River Valley, north-western Madagascar. *Azania*, 31: 37-73.

Yan, H., Wei, W., Soon, W., An, Z., Zhou, W. & Liu, Z. 2015. Dynamics of the intertropical convergence zone over the western Pacific during the little ice age. *Nature Geoscience*, 8: 315-320.

Zachos, J., Pagani, M., Sloan, L., Thomas, E. & Billups, K. 2001. Trends, rhythms, and aberrations in global climate 65 Ma to present. *Science*, 292: 686-693.

Zhang, C. 1993. On the annual cycle in highest, coldest clouds in the tropics. *Journal of Climate*, 6: 1987-1990.

Zhang, R. & Delworth, T. L. 2005. Simulated tropical response to a substantial weakening of the Atlantic thermohaline circulation. *Journal of Climate*, 18: 1853-1860.

Zheng, X.-T., Xie, S.-P., Du, Y., Liu, L., Huang, G. & Liu, Q. 2013. Indian Ocean dipole response to global warming in the CMIP5 Multimodel Ensemble. *Journal of Climate*, 26: 6067-6080.

Zinke, J., Loveday, B. R., Reason, C. J. C., Dullo, W. C. & Kroon, D. 2014. Madagascar corals track sea surface temperature variability in the Agulhas Current core region over the past 334 years. *Scientific Reports*, 4: 4393.