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# The Malagasy monsoon over the Holocene: A review from speleothem $\delta^{18}\text{O}_c$ records

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## **Abstract**

Speleothem stable oxygen isotope records ( $\delta^{18}\text{O}_c$ ) are among fundamental proxies in paleoclimate reconstruction. Most generally, speleothem  $\delta^{18}\text{O}_c$  reflects the  $\delta^{18}\text{O}_w$  of the feeding drip water, which in turn is closely linked to the  $\delta^{18}\text{O}_w$  of the water seeping into the cave that mainly originates from atmospheric precipitation. The  $\delta^{18}\text{O}$  of atmospheric precipitation could in turn reflect the  $\delta^{18}\text{O}$  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  $\delta^{18}\text{O}_c$  from Anjohibe Cave, in NW Madagascar, to record information about its past climate, starting from reporting on the modern cave investigation on speleothem  $\delta^{18}\text{O}_c$ , drip water  $\delta^{18}\text{O}_w$  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. It will also attempt to review the challenges in the interpretation of the 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.

## Résumé:

Les enregistrements des isotopes stables d'oxygène dans les spéléothèmes ( $\delta^{18}\text{O}_c$ ) sont parmi les proxys fondamentaux dans la reconstruction du paléoclimat. Plus généralement, le  $\delta^{18}\text{O}_c$  reflète la  $\delta^{18}\text{O}_w$  de l'eau au goutte-à-goutte, qui est à son tour étroitement liée au  $\delta^{18}\text{O}_w$  de l'eau s'infiltrant dans la grotte qui provient principalement des précipitations atmosphériques. Les  $\delta^{18}\text{O}$  des précipitations atmosphériques pourraient à leur tour refléter les  $\delta^{18}\text{O}$  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 divers entités, de la grotte à l'atmosphère, pourrait expliquer l'avantage des spéléothèmes en tant qu'enregistreur d'informations fiables sur le climat passé.

Cet article vise à examiner le potentiel du  $\delta^{18}\text{O}_c$  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  $\delta^{18}\text{O}_c$  du carbonate, le  $\delta^{18}\text{O}_w$  de l'eau d'infiltration et de sa température, pour comprendre la comportement global du mousson dans l'île, qui est actuellement connue comme le moteur de la saisonnalité à Madagascar, principalement dans sa partie ouest. L'article tentera 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.

## 1. 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 (e.g., Hondula et al., 2012; Heath, 2010), and a slight increase ( $\sim 0.2$  to  $0.8^{\circ}\text{C}$ ) in temperature might negatively impact the agricultural activity in some regions (e.g., 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 (e.g., UNICEF, 2019). Extensive drought causes negative impacts on food production and human welfare worldwide (e.g., Cane et al., 1994) and decreases political stability (e.g., Benson and Clay, 1998). Humans are not the only ones affected by climate change, but also fauna and flora, particularly endemic species (e.g., Thuiller et al., 2006; Barrett et al., 2013) and coral reefs (e.g., 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 (e.g., 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 (e.g., Kim and O'Neil, 1997; Hansen et al., 2019). This is particularly relevant for paleoclimate and paleoenvironmental reconstruction, using stalagmites as one example (e.g., Day and Henderson, 2011; Hansen et al., 2019). Stalagmites, a form of speleothems (=secondary cave deposits), are considered reliable geological archives in paleoclimate reconstruction (Fairchild and Baker, 2012; Wong and 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 (e.g., 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  $\delta^{18}\text{O}_c$  from Anjohibe Cave, in NW Madagascar, 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  $\delta^{18}\text{O}_w$ , which is assumed to be reflected in the cave drip water  $\delta^{18}\text{O}_w$  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  $\delta^{18}\text{O}_c$  signals. Because speleothem  $\delta^{18}\text{O}_c$  strongly depends on the temperature at which it grows and the drip water  $\delta^{18}\text{O}_w$  from which it precipitates, this review will also report on a recent investigation performed in Anjohibe Cave. Such investigation mainly includes measurement of speleothem  $\delta^{18}\text{O}_c$ , drip water  $\delta^{18}\text{O}_w$  and temperature, to understand isotopic fractionation. Information about this isotopic fractionation is crucial to ensure that speleothems  $\delta^{18}\text{O}_c$  are reliable recorders of past climate change. With this knowledge, the available speleothem  $\delta^{18}\text{O}_c$  data published from Anjohibe Cave are compiled to deduce a more comprehensive understanding of the overall monsoonal behavior in the island. 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, 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.

## **2. 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 (e.g., 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 “monsoons” 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 (e.g., the Eurasian continent) and

oceans (e.g., 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 and 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 and 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 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 and Friedman, 2012). Beyond instrumental records, changes

in the relative position of the ITCZ have been investigated via climate modeling (Broccoli et al., 2006; Frierson and Hwang, 2012; Kang et al., 2008) and has 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 (e.g., 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 (e.g., Yan et al., 2015; Denniston et al., 2016; Donohoe et al., 2019).

Of relevance to this review 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.

### **3. 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 entire country (Figure 3) (Jury, 2003; DGM, 2008). This gradient could



be explained by the N-S 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 mountain 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 and 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 and Kottek., 2010). Rainfall is typically recorded between November and March (Jury, 2003). The study region of interest in this review 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).

## 4. Rainfall $\delta^{18}\text{O}$ in Madagascar

### 4.1. Potential influence of the seasonality and the island's topography

Although rainfall  $\delta^{18}\text{O}$  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  $\delta^{18}\text{O}_w$  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  $\delta^{18}\text{O}$  ( $r^2=0.33$  and  $0.35$ , respectively; see Voarintsoa et al., 2017b), in a sense that rainfall during cooler and drier months is more enriched in  $^{18}\text{O}$  than rainfall during warmer and wetter months. Given the current topography of Madagascar and its current geographic position relative to the ITCZ, the seasonal variability of the island's rainfall  $\delta^{18}\text{O}_w$  is assumed to be influenced closely by the "amount effect", which means more negative  $\delta^{18}\text{O}_w$  during rainier months (e.g., Dansgaard, 1964; Risi et al., 2008; McDermott, 2004; Lachniet, 2009). With this logic, summer rainfall should be more depleted in  $^{18}\text{O}$  than winter rainfall.

Using the available rainfall  $\delta^{18}\text{O}_w$  data from Antananarivo and other rainfall  $\delta^{18}\text{O}_w$  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 and Wilkinson (2002) and refined by Bowen and 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).

#### **4.2. Potential influence of the moisture source/atmospheric-circulation**

The majority of moisture sources in Madagascar originate from western Indian Ocean (~~mainly for its eastern part~~). In addition to this, the other regions of Madagascar might receive their moisture sources either from North of the Mozambique Channel, e.g., the northern, northwestern, and western Madagascar or south of the Mozambique Channel (such as the Agulhas 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 (e.g., Saji et al., 1999). During positive IOD events, when eastern Indian Ocean is cooler and western Indian Ocean is warmer, eastern Africa receives more rainfall (e.g., 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 Agulhas Current is strongly connected to the global conveyor belt, also known as the Atlantic Meridional Overturning Circulation, or AMOC (e.g., 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

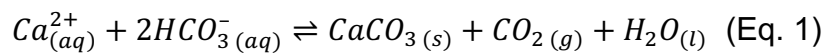
Ocean (e.g., Alley et al., 1997; Alley and Agustsdottir, 2005). Typical events are the 8.2 ka event (e.g. Thomas et al., 2007), the Younger Dryas (e.g. Alley, 2000), the Heinrich events (e.g., Cacho et al., 1999; McGee et al., 2014), and the Dansgaard-Oeschger oscillations (e.g. Cacho et al., 1999). 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 (e.g. Zinke et al. 2014).

## 5. Speleothems

Speleothem minerals are highly variable but calcium carbonate, particularly calcite and aragonite, are the most abundant (Hill and 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.  $\text{CaCO}_3$  precipitation occurs mainly by  $\text{CO}_2$  degassing of the drip water, leading to an increase of its  $\text{CO}_3^{2-}$  concentration and pH (evaporation could also play an additional role, increasing its  $\text{Ca}^{2+}$  concentration). Degassing occurs because the  $\text{CO}_2$ -saturated water percolating down to the cave meets the cave air, the  $p\text{CO}_2$  of which is relatively low compared to that of the drip water. The fundamental equation for stalagmite deposition is shown in Eq. 1, and a simplified sketch describing its process of formation is shown in Figure 7. Equation 1 is maintained in equilibrium when  $\text{CO}_{2(g)}$  and  $\text{Ca}^{2+}$  are proportionately in equilibrium. This

equation explains that an increase in  $\text{Ca}^{2+}$  in the drip water leads to stalagmite deposition, as the water becomes supersaturated with regard to  $\text{CaCO}_3$ .



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 and 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 and 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 was 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 (e.g., Cruz et al, 2007; Voarintsoa et al., 2017a).

## 6. Speleothem $\delta^{18}\text{O}_c$ and what it could represent

Stable isotopes of oxygen, denoted  $\delta^{18}\text{O}$ , are among fundamental proxies used in paleoclimate studies, either in the study of coral records (e.g. Zinke et al., 2014), ice core records (e.g., Thomas et al., 2007), or stalagmite records (e.g. Fleitmann et al., 2004a). For

stalagmites, scientists originally hoped to use their  $\delta^{18}\text{O}_c$  signatures as an indicator of paleotemperature, as carbonate isotopic composition is mainly controlled by two main factors including temperature and  $\delta^{18}\text{O}$  of the parent water (e.g., Urey, 1947; Emiliani, 1966), but later realized that  $\delta^{18}\text{O}_c$  of stalagmites is controlled by a complex combination of several factors (e.g., McDermott, 2004; Lachniet, 2009). Indeed, interpretations of speleothem  $\delta^{18}\text{O}_c$  time series may be quite complex. Speleothem  $\delta^{18}\text{O}_c$  typically reflects the  $\delta^{18}\text{O}_w$  of the feeding drip water, which in turn is closely linked to the  $\delta^{18}\text{O}_w$  of the water seeping into the cave that mainly originates from atmospheric precipitation (e.g., Burns et al., 2002; Fairchild and McMillan, 2007). The  $\delta^{18}\text{O}$  of atmospheric precipitation could in turn reflect the  $\delta^{18}\text{O}$  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  $\delta^{18}\text{O}$ -value of the ocean, because thicker ice shields might concentrate  $^{16}\text{O}$  more than smaller ones. The change in global sea level as a function of cold and warm periods can influence the  $\delta^{18}\text{O}$  value of the source water (e.g. Zachos et al., 2001). This can later be transferred to the  $\delta^{18}\text{O}$  signals in precipitation and then to cave drip waters, from which speleothems precipitate (e.g., Lachniet, 2009, p. 424).

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

Immediate controls on  $\delta^{18}\text{O}_c$  variability in speleothems include  $\delta^{18}\text{O}_w$  of the drip water which could vary depending on the  $\delta^{18}\text{O}_w$  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  $\delta^{18}\text{O}_c$ , as lighter oxygen isotopes ( $^{16}\text{O}$ ) are removed from the drip water to the vapor in the cave atmosphere. The influence of cave temperature on  $\delta^{18}\text{O}_c$  is not easily detectable in a single cave as the cave mean annual temperature is commonly stable and represent 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 between each other (e.g., 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.

## 7. Speleothem records in Madagascar

Over the past five years, at least six speleothems have produced high resolution  $\delta^{18}\text{O}_c$  records from Anjohibe Cave (Figure 8) to uncover past climate and past environmental change in NW 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).

### 7.1. Speleothem modern information

To ensure that speleothem  $\delta^{18}\text{O}_c$  is a reliable recorder of past climate change, measurement of modern speleothem  $\delta^{18}\text{O}_c$ , drip water  $\delta^{18}\text{O}_w$ , 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  $\delta^{18}\text{O}_c$  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 (e.g., Kim and O'Neil., 1997). Furthermore, the calculated isotopic fractionation factors between speleothem carbonates and their parent water ( $^{18}\alpha_{\text{CaCO}_3\text{-H}_2\text{O}} = (\delta^{18}\text{O}_c, \text{VSMOW} + 1000) / (\delta^{18}\text{O}_w, \text{VSMOW} + 1000)$ ) fit well within the global fractionation curve as a function of temperature (Figure 9) that was first reported by Tremaine et al. (2011),  $1000 \ln ^{18}\alpha = 16.1 (10^3/T(^{\circ}\text{K})) - 24.6$ , and



followed by Johnston et al. (2013),  $1000 \ln^{18}\alpha = 17.66 (10^3/T(^{\circ}\text{K})) - 30.16$ . 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  $\delta^{18}\text{O}_c$  from Anjohibe Cave for further paleoclimate study.

## **7.2. Speleothem paleo-records**

A broad screening of the  $\delta^{18}\text{O}_c$  records of each published stalagmite from Anjohibe Cave (Figure 10) can suggest a relatively stable hydroclimate in northwestern Madagascar, with much of the  $\delta^{18}\text{O}_c$  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 Section 7.2.2). On a bigger scale, the hydroclimate variability in NW Madagascar potentially supports the latitudinal migration of the ITCZ, influencing the length of its visit in either hemisphere during the migration (e.g., Chiang and Bitz, 2005; Broccoli et al., 2006), that could be in or out of phase with the expansion or contraction of the rain belt (e.g., Yan et al., 2015; Denniston et al., 2016).

The Holocene records from stalagmite ANJB-2 and ANJ94-5 suggests 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<sub>3</sub> 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<sub>3</sub> deposition after ca. 1.6 ka BP, the “Malagasy late Holocene interval” or MLHI. Each of these intervals of deposition records different isotopic signals (see Fig. 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 surrounding landscape in NW Madagascar (Burns et al., 2016; Voarintsoa et al., 2017b, see also references therein).

Voarintsoa et al. (2017c) used the distinct intervals of stalagmite depositions (see their Fig. 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 (deMenocal et al., 2000), 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 reflecting 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)—and hence reflecting a weaker monsoon as a result of a northward migration of the ITCZ, agreeing with the model of Braconnot et al. (2007).

### **7.2.1. 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  $\delta^{18}\text{O}_c$  records, applying the Bartlett power spectrum using the Analyseries software 2.0.8 of Paillard et al. (1996), suggest 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  $\delta^{18}\text{O}_c$  is evident around  $7.3 \pm 0.1$  ka BP, which is additionally marked by the presence of aragonite (Wang et al., 2019), a mineral that is used as indicator of dry conditions in speleothem (e.g., Murray, 1954; Thrailkill, 1971; Cabrol and Coudray, 1982; Railsback et al., 1994; Frisia et al., 2002). The 600–800-year periodicity could reflect the sub-millennial dynamics of the ITCZ (e.g., 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 NW 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.

### **7.2.2. 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 (e.g., Alley et al., 1997; Barber et al., 1999), that was marked by regional cooling in the North Atlantic and surrounding regions (e.g., Alley et al., 1997; Klitgaard-Kristensen et al., 1998; Barber et al., 1999; Alley and Agústsdottir, 2005). This abrupt climate perturbation altered the density and salinity of the North Atlantic Deep Water (e.g., Thornalley et al., 2009), weakening the AMOC (e.g., Clark et al., 2001; Renssen et al., 2001; Dong and Sutton, 2002; Vellinga and Wood, 2002; Zhang and Delworth, 2005), leading to widespread cooling in the NH regions (e.g., Clark et al., 2001; Thomas et al., 2007) but warming in the SH regions (Wiersma and Renssen, 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 8.22 to 8.48 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 NW 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'  $\delta^{18}\text{O}$  values, stalagmites  $\delta^{18}\text{O}_c$  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 (e.g., Dominguez-Villar et al., 2009).

### **7.2.3. The mid-Holocene**

In contrast to the MEHI, the mid-Holocene interval in NW 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 NH, could suggest that the southernmost boundary of the ITCZ may barely touched part of NW Madagascar, leading to a weakening of the Malagasy Monsoon. It could also mean that summer seasons in NW Madagascar 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, 5.2 ka, and from 4.3ka to 4.0 ka) to express global Rapid Climate Change (RCC) at 5.2ka 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 Mayweski et al. (2004). The causes and mechanisms behind these cool poles–dry tropics are still poorly understood.

#### **7.2.4. 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 (e.g., Burney and MacPhee, 1988,

Burney et al., 1997; Dewar and Richards, 2012; Godfrey et al., 2019). This led recent researchers to investigate closely the differences between pristine vs. anthropogenic induced landscape by looking at speleothem  $\delta^{13}\text{C}_c$  (e.g., Burns et al., 2016; Voarintsoa et al., 2017b), sediment core proxies (e.g., Matsumoto and Burney, 1994),  $\delta^{15}\text{N}$  values from radiocarbon-dated subfossil vertebrates (e.g., Crowley, 2010; Crowley and Samonds, 2013), and archaeological evidence (e.g., 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 (e.g., Crowther et al., 2016) to settle in the island.

As a whole, the late Holocene stalagmite  $\delta^{18}\text{O}_c$  records from Anjohibe Cave show 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, p.150) and Scroxton et al. (2017, p.31). With higher resolution records, Scroxton et al. (2017) found a dominant  $\delta^{18}\text{O}_c$  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  $\delta^{18}\text{O}_c$  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  $\delta^{18}\text{O}_c$  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 NW Madagascar in response to changing climate in regions of the northern Hemisphere (exemplified by the changing temperature records in Europe; e.g., Büntgen et al., 2011), i.e., with more rainfall during longer visit (thus more negative  $\delta^{18}\text{O}_c$ ), 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, either the latitudinal migration of the ITCZ or its contraction/expansion could be expected to influence monsoon hydroclimate in Madagascar, as both 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  $\delta^{18}\text{O}_c$  values between 800 and 1400 CE in the overall records may, in fact, reflect wetter conditions when the ITCZ moves relatively south, and potentially an enhanced summer season

With all the records of  $\delta^{18}\text{O}_c$  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 of which are the sub-millennial periodicity (~800–1000 years), the sub-centennial periodicity (~100–200 years), and the multidecadal periodicity (~30–50 year), each potentially reflecting monsoonal changes, but with varying forcing mechanisms, e.g., interhemispheric difference in temperature leading to the latitudinal migration of the ITCZ (e.g., Chiang and Friedman, 2012) and potentially influencing the monsoon circulation in the Indian Ocean (e.g., Schott and McCreary, 2001),



insolation (e.g., Kutzbach and Liu, 1997; Partridge et al., 1997), changes in sea surface temperature that may be linked to the Indian Ocean Dipole (e.g., Saji et al., 1999; Zheng et al., 2013), or changes in the Walker circulation that may have caused the contraction and the expansion of the ITCZ over the western Indian Ocean.

From a closer observation of the late Holocene speleothem  $\delta^{18}\text{O}_c$  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  $\delta^{18}\text{O}_c$  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  $\delta^{18}\text{O}_c$  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 cease 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 NW 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 NW Madagascar with this northward shift of the ITCZ toward a warmed NH, suggests that climate in Mahajanga could become drier if this northward migration of the ITCZ continues for the next century.

## 8. Challenges in proxy interpretation and future directions

To reconstruct the past climate and environment 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 rely on the lack of long-term monitoring linking rainfall  $\delta^{18}\text{O}_c$  and drip water  $\delta^{18}\text{O}_w$ . The information from such investigation could subsequently help us better understand how geochemical signals are recorded in speleothems, and how these signals link to climate (e.g., van Breukelen et al., 2008). The global challenge in the calibration of speleothem  $\delta^{18}\text{O}_c$  with modern rainfall to estimate paleorainfall is that the speleothem  $\delta^{18}\text{O}_c$  and rainfall  $\delta^{18}\text{O}_w$  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  $\delta^{18}\text{O}_c$  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 have been recently initiated in Anjohibe Cave, which measures the modern carbonate precipitates  $\delta^{18}\text{O}_c$ , the drip water  $\delta^{18}\text{O}_w$  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, which further implies the significant influence of in-cave temperature on speleothem  $\delta^{18}\text{O}_c$  regardless of other factors that may also influence the variability of  $\delta^{18}\text{O}_c$ . As noted earlier, although the other potential controls on the kinetic isotope fractionation in Anjohibe Cave are not fully understood, relative to other cave locations elsewhere, this general consistency could be an important key to move forward in using speleothem records as paleoclimate proxy. It could be combined with other proxies for reconstructing temperature (clumped isotopes,  $\Delta_{47}$ ; e.g., Kluge et al., 2013) and for reconstructing past relative humidity, which could strongly shed lights on the notion of moisture sources (triple oxygen isotopes,  $\Delta^{17}\text{O}$  or  $^{17}\text{O}_{\text{excess}}$ ; e.g., Sha et al., 2020; Voarintsoa et al., 2020b), hence providing a more complete picture of the drivers of the oxygen isotopes variability in limestone cave 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 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  $^{234}\text{U}$  and  $^{230}\text{Th}$  on Faraday cups (e.g., Cheng et al., 2013). Others have used the relationship between  $^{230}\text{Th}/^{232}\text{Th}$  values and  $^{232}\text{Th}$  concentrations

from the topmost layers of a stalagmite to correct the age with a unique  $^{230}\text{Th}/^{232}\text{Th}$  value (Ridley et al., 2015). Strong knowledge of the sample's petrography has also become powerful to refine the U-Th based chronology (e.g., 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.

## 9. Conclusion

Approaches to using speleothem  $\delta^{18}\text{O}_c$  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–c, 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 (e.g., Scroxton et al., 2017). Combining the modern speleothem  $\delta^{18}\text{O}_c$ –temperature calibration (Section 7.1) with the widely agreed “amount effect” influence on tropical rainfall  $\delta^{18}\text{O}_w$ , 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 suggest that negative speleothem  $\delta^{18}\text{O}_c$  values are indicative of stronger monsoon, whereas positive speleothem  $\delta^{18}\text{O}_c$  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 (Section 8), speleothem  $\delta^{18}\text{O}_c$  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.

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## Figure and table captions

**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 the map of Wang (2009), which was originally redrawn from Wang and Ding (2008). The two red lines represent the seasonal mean position of the ITCZ during austral winter (north) and summer (south).

**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  $0.25^\circ \times 0.25^\circ$  3B43 merged TRMM and other sources estimate data. The images cover the globe from  $40^\circ$  North to  $40^\circ$  South. (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 and Wells, 2003). Note the North-South and East-West gradient in rainfall and temperature during summer (January) and winter (July) seasons.

**Figure 4:** Meteogram climate from a weather station in Mahajanga over at least the past ten 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](http://www.meteoblue.com)).

**Figure 5:** Time series of (a) rainfall and  $^{18}\text{O}$  and (b) temperature and  $\delta_{18}\text{O}$  observed and measured from Antananarivo, Madagascar. (Lat.  $18^\circ 54' 00''$ ; Long.  $047^\circ 31' 48''$ ; Alt. 1300 m) showing that drier winter seasons are marked with higher  $\delta^{18}\text{O}$  values, whereas wetter summer seasons with more negative  $\delta^{18}\text{O}$ . 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).

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

**Figure 7:** Generalized sketch showing the processes of stalagmite formation (from dissolution, degassing and/or evaporation of the drip water, to  $\text{CaCO}_3$  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)

**Figure 8:** Time coverage of each published stalagmite  $\delta^{18}\text{O}_c$ . Stalagmites 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  $^\circ\text{K}$ ). The data from Anjohibe Cave, in Madagascar, are shown in blue circle 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).

**Figure 10:** Box plot showing the range of  $\delta^{18}\text{O}_c$  of the published stalagmites from Anjohibe Cave. Indicated in grey are the two Holocene samples.

**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.

**Figure 12:** Late Holocene time series of all available speleothem  $\delta^{18}\text{O}_c$  data from Anjohibe Cave. Highlighted in cyan is the interval of "favorable condition" discussed in Voarintsoa et al. (2017b) when climate conditions favored foreign migrants to settle in Madagascar. The increased trend after ca. 1750-year CE could be an evidence of a warming trend.

**Figure 13:** Periodogram runs on all available speleothem  $\delta^{18}\text{O}_c$  from Anjohibe Cave. Note that AB2b is the same stalagmite as AB2, but I added the extra label "b" simply to differentiate the high (Scroxton et al., 2017) vs. low resolution records (Burns et al., 2016).

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



# Figures

Figure 1

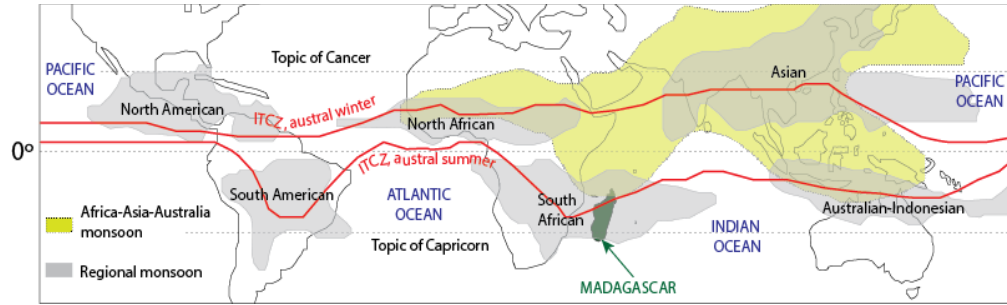


Figure 2

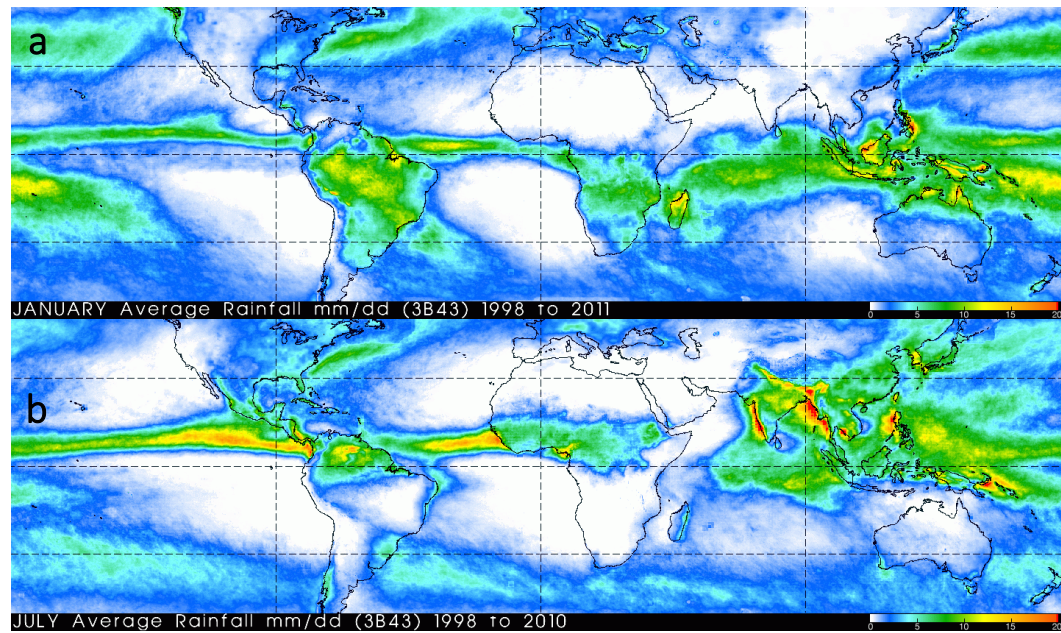


Figure 3

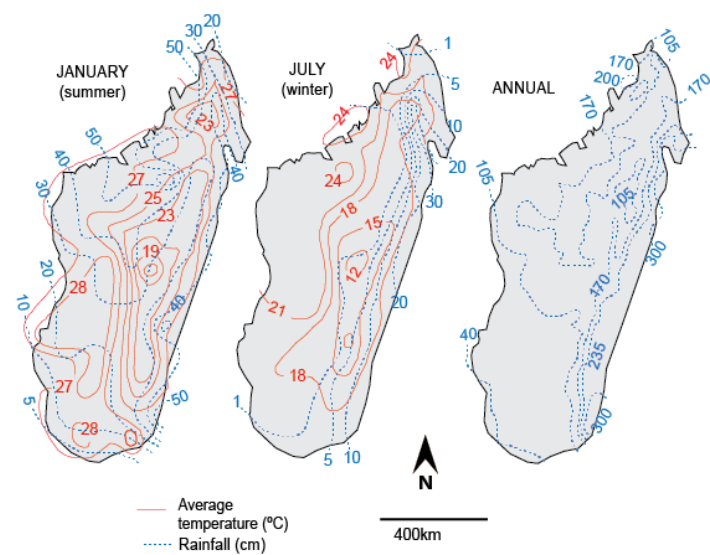


Figure 4

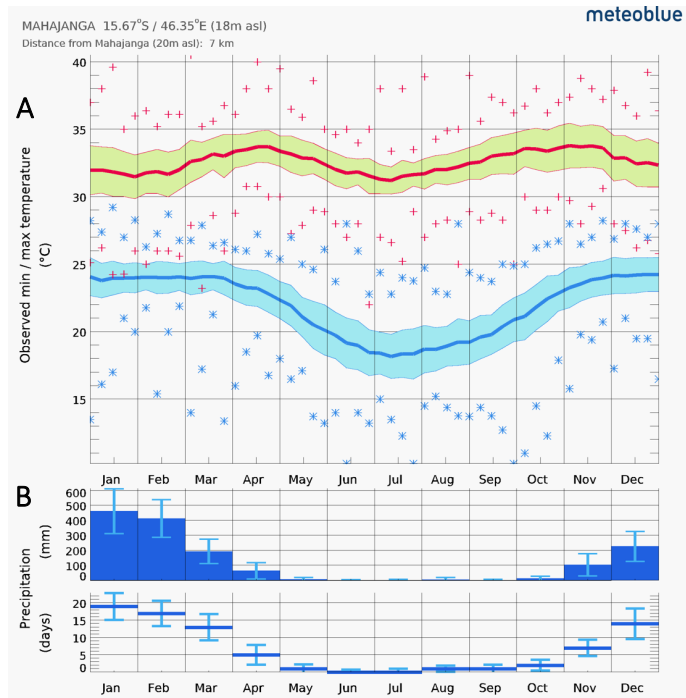


Figure 5

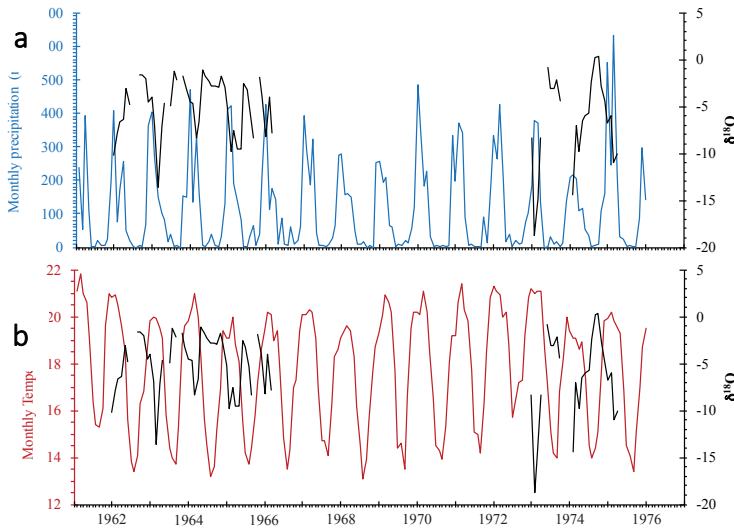


Figure 6

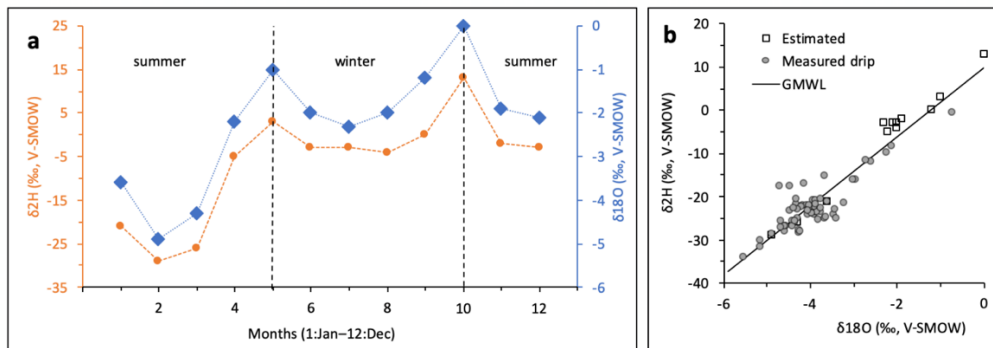


Figure 7

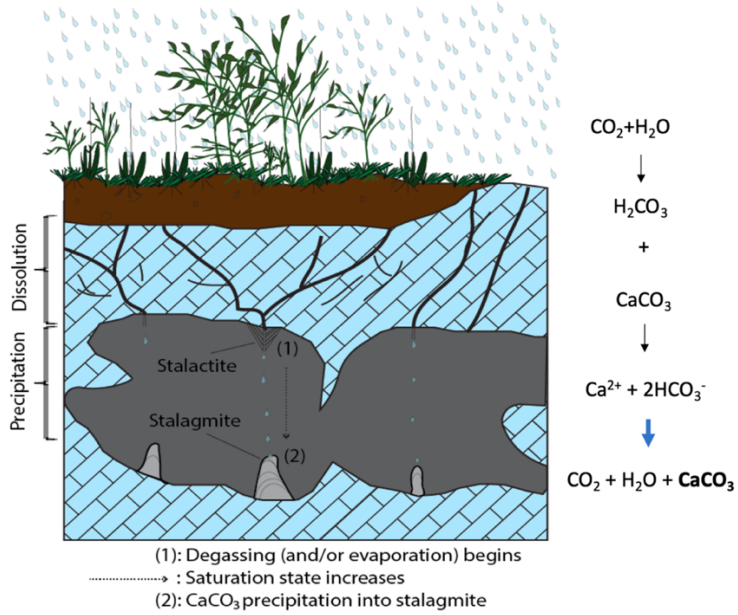


Figure 8

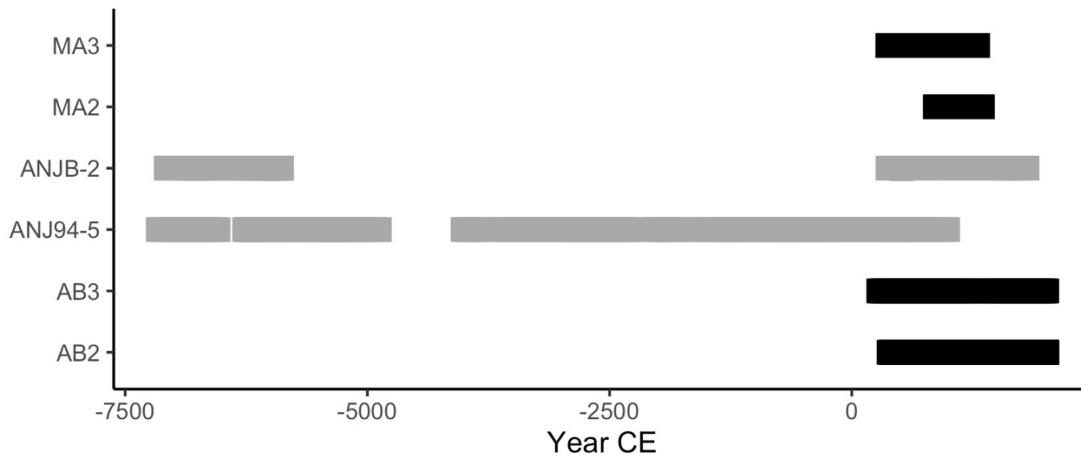


Figure 9

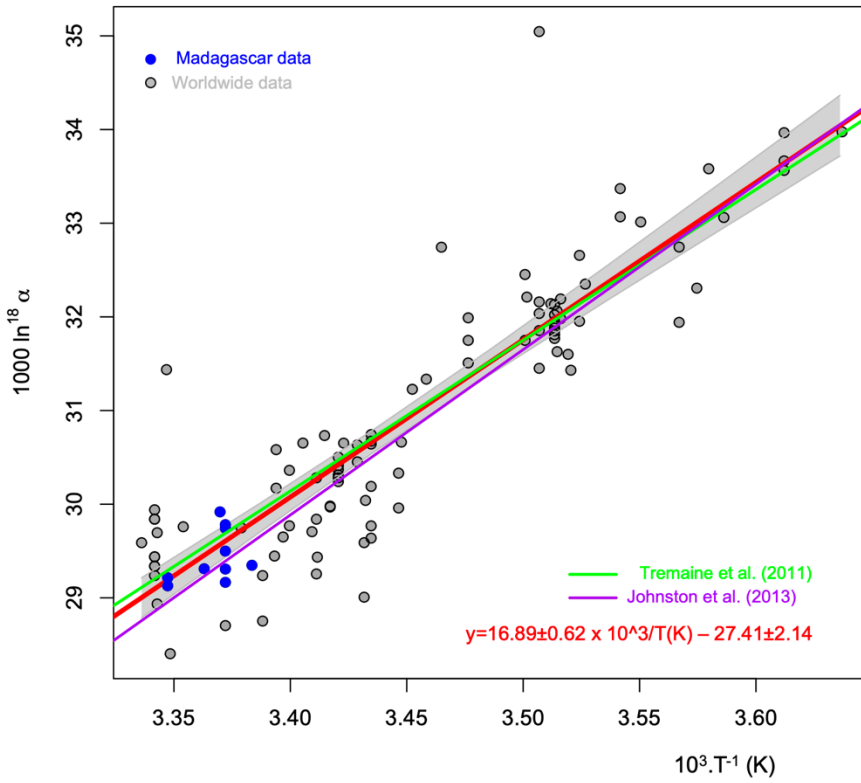


Figure 10

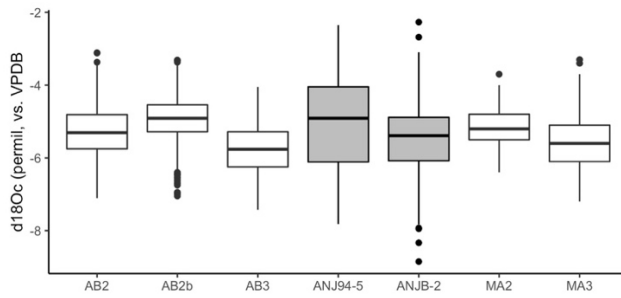


Figure 11

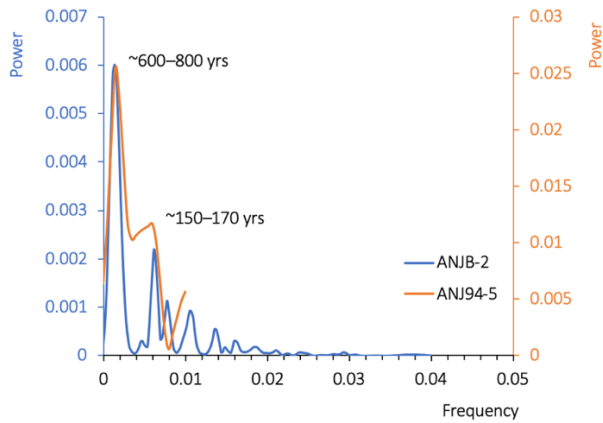


Figure 12

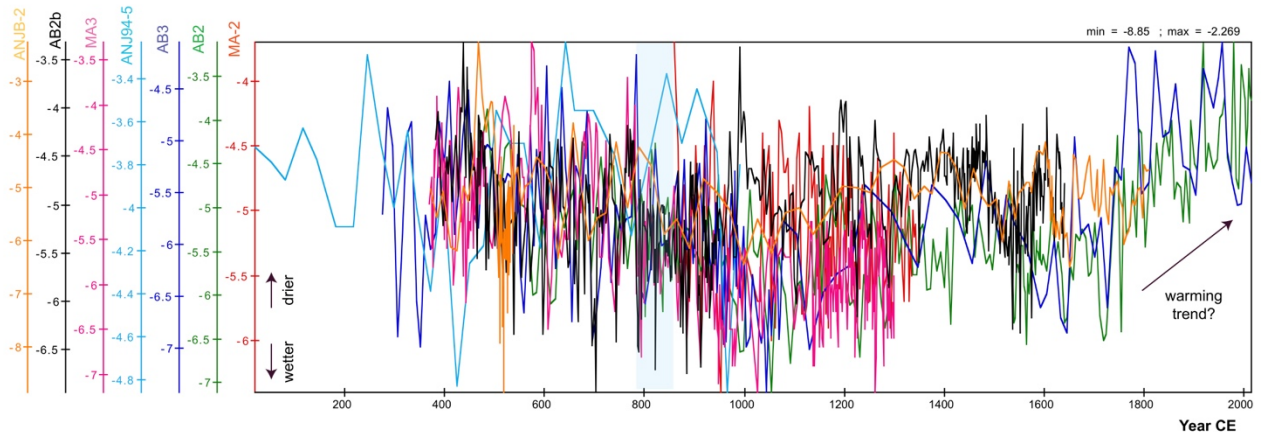


Figure 13

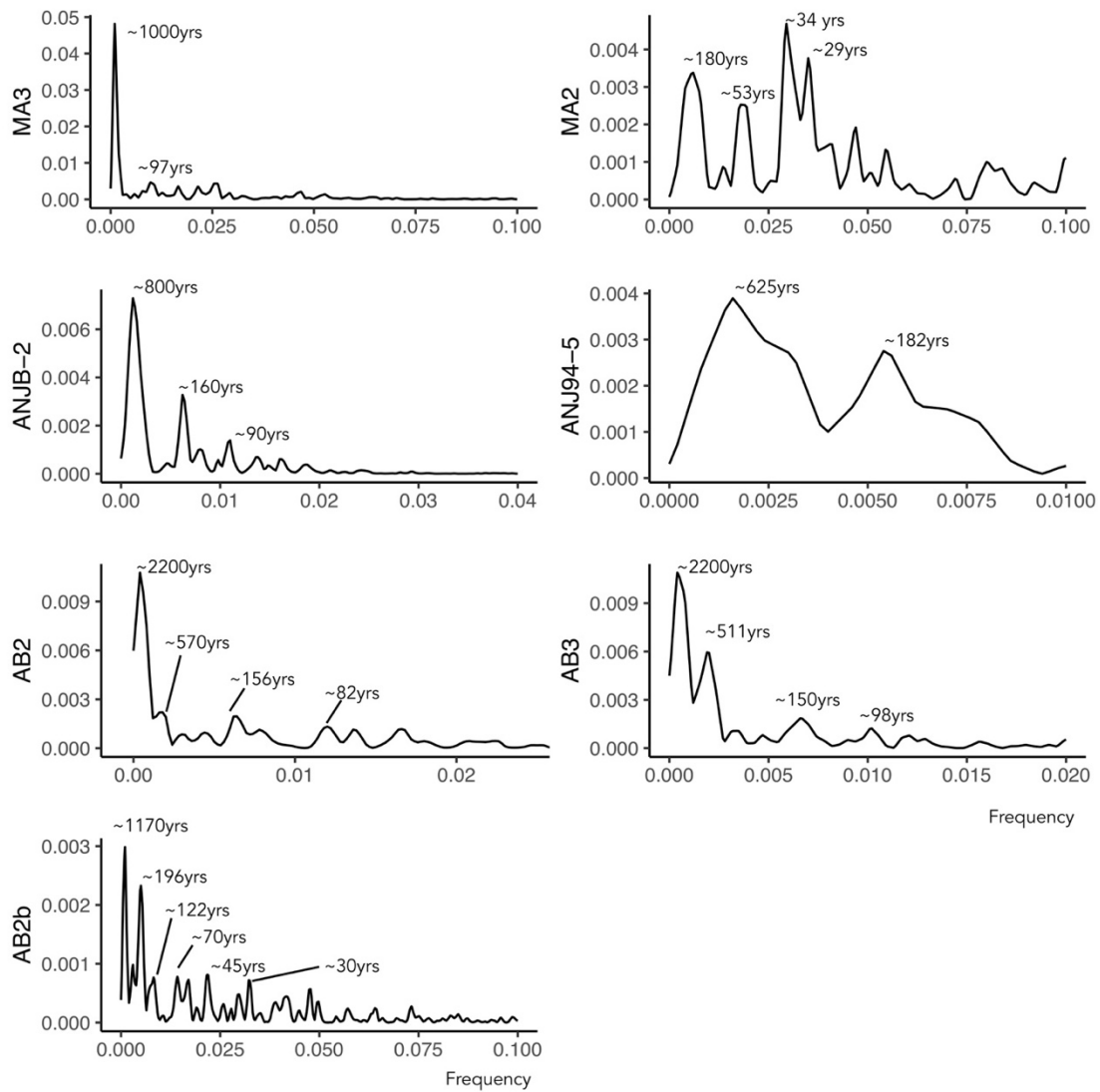


Table 1

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