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Hemispherically in-phase precipitation variability over the last 1700 years in a Madagascar speleothem record

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ABSTRACT

Paleoclimate studies of tropical rainfall have led to a recognition of a predominant pattern of anti-phase behavior between the Northern and Southern hemispheres at both orbital and millennial timescales. Less certain is how regional tropical rainfall patterns have changed in the late Holocene, under boundary conditions and on timescales which are most relevant to the tropics' response to a warming world. Several high-resolution southern hemisphere rainfall records are at odds with meridional movement of the mean Inter-Tropical Convergence Zone location as the major driver of Holocene tropical rainfall variability, with regional precipitation patterns resembling modern day El-Niño Southern Oscillation end members. To test emerging ideas on sub-millennial tropical rainfall variability, additional records from the southern hemisphere are required.

We present a new speleothem $\delta^{18}O$ record from Anjohibe Cave, northwestern Madagascar, which provides a quasi-annual record of monsoonal strength and precipitation amount for the last 1700 years. The majority of $\delta^{18}O$ variability in the record is at the decadal scale, and shows little to no correlation with major climate indices or cyclical climate drivers. At lower frequencies, changes in mean speleothem $\delta^{18}O$ show good correlation with other regional precipitation records both north and south of the equator. The regional coherency of tropical rainfall across the west Indian Ocean resembles expansion and contraction of the tropical rain belt and positive-Indian Ocean Dipole-like conditions at different timescales. The cause of this coherency could be related to symmetrical changes in continental sensible heating, or to a low frequency sea surface temperature climate mode.

1. Introduction

Year to year variation in rainfall has a dramatic impact on the health and prosperity of people in the tropics, particularly in socioeconomically vulnerable regions such as eastern Africa (Hashizume et al., 2009). Despite some recent improvements, Madagascar is one of the ten poorest countries in the world, with a per capita GDP of $443 (World Bank, 2015), 70% of the population living in poverty and the fourth lowest access to water in Africa (UNICEF, 2012). Four out of five people are dependent on rain fed agriculture (Macron et al., 2016). Madagascar is particularly vulnerable to hydrological natural disasters with frequent tropical cyclones, droughts and flooding. One quarter of the population resides in zones rated at risk of natural disasters (GFDRR, 2013). Understanding of hydrological variability in Madagascar is therefore critical to the lives and wellbeing of millions in this understudied region. Yet instrumental records of rainfall in Madagascar are short and frequently discontinuous, hindering understanding of what factors influence rainfall variability on interannual and longer timescales.

The seasonal and spatial distribution of Madagascan rainfall is largely controlled by two factors: the central massif along eastern Madagascar, which consists of a broad 1200 m high plateau with peaks up to 2876 m, and the annual migration of the ITCZ. During austral winter the Mascarene high to the southeast of Madagascar brings onshore trade wind easterlies to the island (Fig. 1). The central massifs create orographic rainfall on the east coast and a

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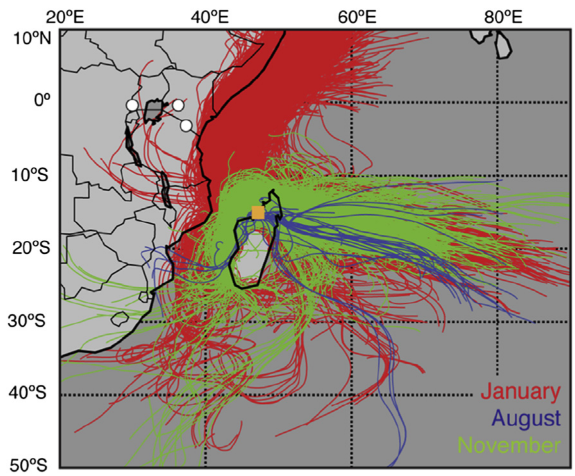

Fig. 1. Air parcel 120hr back trajectory simulations indicating likely moisture source areas for precipitation at Anjohibe (yellow rectangle). Trajectories shown for wet season (January, red), shoulder season (November, green) and dry season (August, blue). Trajectories were launched at 500, 1000 and 1500 m every 6 h for GDAS data between 2005 and 2015 using Python package PYSPLIT (Cross, 2015) on top of the NOAA HYSPLIT model (Stein et al., 2015). Only rain bearing trajectories and those with a forward integration error of less than 10% were used. White circles indicate other paleoprecipitation records discussed in the text. From west to east: Lake Edward, Lake Naivasha, Lake Challa.

rain shadow to the west that extends across the entire island. The result is a strong east to west rainfall gradient. During austral summer the Mascarene high weakens and retreats to the southeast whilst the ITCZ moves southwards into the Mozambique channel reaching 15°S (Jury and Pathack, 1991). Northwesterly winds bring monsoonal rains to most of the island and create a strong north to south rainfall gradient. Northwestern Madagascar is therefore insulated against trade-wind derived precipitation and exposed to variability in the monsoon.

Interannual variability of rainfall on Madagascar is not well constrained due to a paucity of lengthy instrumental records. Poor correlation between regional outgoing longwave radiation and Madagascan rainfall (Jury et al., 1993) suggests that local influences dominate Madagascan rainfall. As a consequence, studies using a combination of convection processes and zonal climate modes, such as the Southern Oscillation Index (SOI), Madden Julien Oscillation (Jury et al., 1995), and the Quasi-Biennial Oscillation (Macron et al., 2016), fail to explain much of Madagascan rainfall variability. Links between Madagascan rainfall and El-Niño-Southern Oscillation (ENSO) are typically made by correlation with regional rainfall rather than direct one-to-one association (Brook et al., 1999; Goddard and Graham, 1999).

A major driver of west Indian Ocean hydroclimate and sea surface temperature (SST) variability is the Indian Ocean Dipole (IOD). The IOD is an oscillatory zonal climate mode not dissimilar to ENSO, but largely restricted in its atmospheric influence to the boreal spring (coinciding with the short rains of equatorial East Africa). During positive phases of the IOD an increase in the average east to west SST gradient and wind strength brings wetter austral spring conditions to the equatorial west Indian Ocean (Saji et al., 1999; Webster et al., 1999). The IOD has good correlation and mechanistic links with ENSO, but IOD events can also result from internal Indian Ocean dynamics alone (Goddard and Graham, 1999), suggesting a degree of independence from ENSO (Ashok et al., 2003). IOD atmospheric anomalies are unlikely to influence west Madagsacan rainfall due to the orographic isolation that prevents trade-wind derived precipitation from reaching the western half of the island.

The IOD also influences regional sea surface temperatures, and there is strong evidence for an SST signal in regional precipitation in the west Indian Ocean region, both in the modern and the past in East Africa (Black et al., 2003; Hastenrath et al., 2004; Nakamura et al., 2011; Nash et al., 2016) and South Africa (Jury et al., 1995, 1993). A link between west Indian Ocean SSTs and Madagascan rainfall has also been hypothesized (Brook et al., 1999). However, instrumental records and ERA-interim climate reanalysis show no correlation between monthly SST anomalies and monthly rainfall in northwestern Madagascar, except in December ($r = 0.377$, $p = 0.021$). Due to the seasonal locking of the IOD the maximum interannual variability of SSTs in the west Indian Ocean is typically between September and November, before the Madagascan monsoon season between December and March (Schott and McCreary, 2001). While austral spring SST anomalies can influence austral summer rainfall (e.g. in the Seychelles (Harou et al., 2006)), this appears not to be the case further from the equator in Madagascar.

Lower frequency SST modes may circumvent the seasonal locking of the IOD and influence Madagascan rainfall. At decadal or longer timescales the mean state of the IOD is relatively unknown. Indian Ocean SST records of the last 100 years indicate significant decadal variability in the IOD (Abram et al., 2008; Ault et al., 2009; Nakamura et al., 2009), while millennial scale variations in the mean IOD state and seasonality are expected due to the evolution of the Asian monsoon intensity and ENSO variability through the Holocene (Abram et al., 2007). However, both the power of the IOD at the decadal scale (Ashok et al., 2003, 2004) and its relationship to regional precipitation (Konecky et al., 2014) is non-stationary. Thus, it remains to be determined whether changes in mean west Indian Ocean SST and/or IOD behavior may influence Madagascan rainfall on longer timescales.

In contrast to these zonal climate mechanisms, meridional changes in the monsoon may have a significant impact on interannual rainfall variability in Madagascar. The evidence for meridional ITCZ influences on southern hemisphere tropical rainfall at a variety of timescales is well founded. At millennial and orbital timescales precipitation in monsoonal regions has been shown to be modulated by changes in meridional circulation, typically due to movements in the Inter-Tropical Convergence Zone (ITCZ) (Haug et al., 2001; Liu et al., 2003; Schneider et al., 2014; Verschuren et al., 2009). Periods of higher summer insolation are associated with increased summer monsoon rainfall in both hemispheres, leading to anti-phase behavior of the Northern versus Southern Hemisphere monsoons on precessional timescales (X. Wang et al., 2006; Y. Wang et al., 2008). Similar anti-phased changes in rainfall are associated with rapid millennial-scale changes in temperature in the high northern latitudes during the last glacial period. During stadial events in the Greenland ice cores, the northern hemisphere monsoons weakened while the southern hemisphere monsoons intensified (Ayliffe et al., 2013; Denniston et al., 2013; Kanner et al., 2012; X. Wang et al., 2007).

At sub-millennial timescales, there is debate over whether the ITCZ translates north and south or whether it expands and contracts, widening and shrinking the width of the tropical rain belt. Over the late Holocene both anti-phase (Eroglu et al., 2016) and in-phase (Denniston et al., 2016) behavior have been described for the northern and southern hemisphere counterparts of the East Asian summer monsoons (EASM). Out of phase behavior suggests translation of the ITCZ north and south either due to a shift in the seasonal range or a change in the amount of time spent near one seasonal extreme. In-phase behavior implies a symmetrical expansion and contraction of the tropical rain belt. During the Little Ice Age (LIA) between the 16th and 18th centuries, it is expected that greater cooling of the northern hemisphere drives a more