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High-resolution mid-Holocene Indian Summer Monsoon recorded in a stalagmite from the Kotumsar Cave, Central India

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ABSTRACT

The Indian Summer Monsoon (ISM), a significant part of the global monsoon system, is driven by several climate forcing parameters. With the growing pace of global climate change scenario, there is need to focus on generating more high-resolution records of past monsoon. The ISM reconstructions from Core Monsoon Zone (CMZ) of India, which represents all-India Summer Monsoon Rainfall, are useful for a better understanding of its past variability. Such reconstructions from the CMZ are rather sparse and require detailed study based on various climate proxies. Here, we focus on the reconstruction of ISM variability during the mid-Holocene, based on stalagmite oxygen isotope ratios from the Kotumsar cave, Central India. We show that with decreasing insolation, monsoon started declining at the beginning of the mid-Holocene from 8.5 to 6.5 ka BP, which is also observed in the previous ISM reconstructions with coarser resolutions. However, a gradual increase in the rainfall is observed from 6.5 to 5.6 ka BP, a feature which is also noted in the East Asian Monsoon reconstruction from the Dongge cave. Our record mainly emphasizes on the occurrence of several abrupt weak monsoon events throughout the mid-Holocene. The occurrence of 8.2 and 5.9 ka abrupt weak monsoon events suggest that ISM variability is tightly bound to North-Atlantic Oscillation (NAO). We also demonstrate that ISM during the mid-Holocene was partly sensitive to El-Nino Southern Oscillation (ENSO), and displayed an inverse relationship.

1. Introduction

Speleothems, occurring in wide geographic regions and datable precisely by U-Th mass spectrometry, have proved to be important proxies for deciphering past climate changes (*e.g.*, McDermott, 2004). Oxygen isotopic composition ($\delta^{18}O$) is the most widely used proxy in speleothems and is primarily controlled by changes in precipitation due to amount effect in tropical and sub-tropical regions (Neff et al., 2001; Yadava et al., 2004; Lone et al., 2014; Raza et al., 2017).

Therefore, speleothem form an ideal archive to reconstruct the Indian Summer Monsoon (ISM), and is well established (Yadava and Ramesh, 1999, 2005, 2006; Yadava et al., 2004; Laskar et al., 2013; Sanwal et al., 2013; Kotlia et al., 2014; Lone et al., 2014; Allu et al., 2015; Raza et al., 2017). Although ISM on glacial-interglacial timescale shows extreme fluctuations, its variability during Holocene displays significant centennial and multi-decadal changes. Insolation plays a dominant role in controlling the variability of ISM, on orbital timescales (Leuschner and Sirocko., 2003; Kathayat et al., 2016). Whereas on centennial to millennial timescales, ISM variability is observed to co-vary with changes in the North-Atlantic circulation and ENSO (Fleitmann et al., 2003; Hong et al., 2003; Wang et al., 2005; Abram et al., 2007; Kumar and Ramesh, 2017).

Steig (1999) suggested that Mid-Holocene climate changes are more complex and require high-resolution, high-quality studies from different localities. These changes are very important as the human's started wide agricultural practices during this time. Driven by changes in solar output many multi-centennial weak monsoon events in Asian monsoon have been reported to have had

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serious consequences on cultural evolution and are in phase with North Atlantic ice-rafting (Wang et al., 2005). These prolonged droughts in ISM during the mid-Holocene are suggested to be caused by regional warming in the Indo-Pacific Warm Pool (IPWP), due to changes in the meridional overturning circulation and Walker Cell position (Prasad et al., 2014). Moreover, a negative Indian Ocean Dipole (IOD) caused by surface cooling of Arabian sea leads to weakened monsoon winds (Saraswat et al., 2013).

The scarce Holocene speleothem records are either from the peripheral domain of ISM (Burns et al., 1998; Neff et al., 2001; Fleitmann et al., 2003, 2004, 2007; Shakun et al., 2007) or of different time windows from peninsular India (Yadava et al., 2004; Yadava and Ramesh, 2005; Sinha et al., 2007; Berkelhammer et al., 2010, 2012; Kotlia et al., 2014). Furthermore, there is no annual to sub-decadal ISM record from the CMZ that can help resolve the actual structure of these prolonged droughts and their controlling factors vis-à-vis their role in cultural evolution.

In order to address the above issues, here we present 3000 years long Mid-Holocene speleothem based ISM variability record from Kotumsar cave located in CMZ of peninsular India. Spanning from 8.5 to 5.6 ka, the novelty of our record lies in its high resolution (sub-annual to sub-decadal) allowing us to understand the structure of prolonged weak ISM events and their role in the societal change in South Asia. Most of these significant shifts in ISM activity are observed to have occurred within few decades followed by multi-centennial prolonged droughts.

2. Regional settings

The Kotumsar cave (19°00′N, 82°00′E, 35 m below ground level) is one of the many caves located in the Kanger Valley National Park, Chhattisgarh (Fig. 1 top) in Central India. It formed by the dissolution of Kanger limestone of the Indrāvati group of rocks of the Mesoproterozoic era (Maheshwari et al., 2005). The lateral extent of the caves is around 330 m with chambers and passages around 20–70 m wide (Yadava et al., 2007). A narrow channel of water passes through the central part of the cave galleries which is fed at the cave entrance during the ISM season (June to September) and terminates in the middle of the cave becoming a part of the underground pathways. Small ponds are seen during the dry seasons, pre-monsoon and post-monsoon (winter), which receive cave drip water and serve as a source of life for the cave biology. Currently, the cave is open to public visit during winter. In the far interior of this cave (Fig. 1 bottom), a few stalagmite pieces were found lying horizontally within a narrow zone (~1–1.5 m of vertical space between the cave roof and the surface of ~1 m raised bedrock). A few stalagmites were recovered from this site in June 2006 CE. Around these stalagmites, layers of fresh carbonate deposition were seen due to which these were lying intact on the surface, although the surrounding was found to be dry at the time of collection. Climatic, geological and geomorphologic setup in this area has favored the formation of many other caves in the vicinity (*e.g.*, Narayana et al., 2014). Paleomonsoon reconstruction studies based on speleothems from the Dandak (~5 km from the Kotumsar cave) spanning 3.5 ka -present (Yadava and Ramesh, 2005) and 1500–600AD (Sinha et al., 2007), and the Gupteshwar caves (~30 km apart) spanning 3.4 ka – present (Yadava and Ramesh, 2005) have been reported earlier.

The nearest meteorological station, Jagadalpur, is ~5 km from the cave (Fig. 1.). To determine the moisture sources contributing to rainfall during the wet season (June to October), we carried out a Lagrangian back trajectory analysis using the HYSPLIT model (Stein et al., 2015) with NCEP Reanalysis-1 (Kalnay et al., 1996) as input to the model. We chose all the days with daily rain above 2 mm during 30years (1980–2009 CE) for the analysis. During ISM, trajectories suggest that the Arabian Sea is the major source of moisture and its isotopic composition is likely to reflect the rainout over the Western Ghats (Fig. 2).

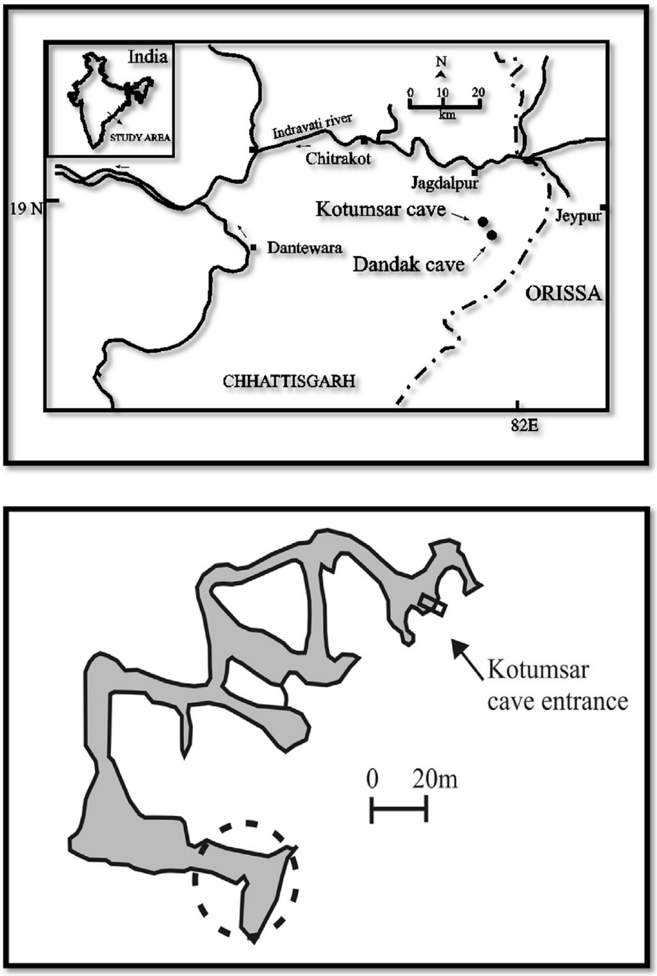

Fig. 1. *Top*: Map of the study area showing the location of the Kotumsar cave, Central India; *bottom*: Sketch of horizontal cross-sectional view of the Kotumsar cave (Yadava et al., 2007). Dotted circle shows the site of KOT-I speleothem.

3. Material and methods

KOT-I sample is a 29.6 cm long stalagmite, composed mostly of white calcite with its outer surface covered by a grey calcitic layer (based on X-ray diffraction analyses). Sample, when cut along its growth axis, can be divided into four bands (I to IV, SI. Fig. 1) based on color and texture. In band III, distinct brown laminae, in response to incorporation of soil impurities, are observed.

Very high-resolution sampling was done using Newwave Research Micromill, with the spatial resolution of 200 μm (~3–5 samples in a layer). Around 1277 subsamples were extracted from 29.6 cm long KOT-I stalagmite. Subsamples weighed ~500 μg and stable isotopes of O were measured on a Delta-V plus IRMS at the Physical Research Laboratory, Ahmedabad, India. The International standard NBS-19 was used for calibration and results are reported with respect to VPDB. The precisions (1σ) of δ^{18}O and δ^{13}C measurements were ~0.09‰ and ~0.1‰ respectively. The stalagmite was sampled at six layers for U-Th dating and the measurements were carried out using a Thermo–Fisher NEPTUNE multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS) at the High Precision Mass Spectrometry and Environmental Change

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