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Precipitation variability in the Indian Central Himalaya during last ca. 4,000 years inferred from a speleothem record: Impact of Indian Summer Monsoon (ISM) and Westerlies

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A B S T R A C T

We report the first high resolution stalagmite record from Indian Central Himalaya by using a combined oxygen and carbon isotopic study spanning the last 4000 years. In addition to the multi-decadal events, the stalagmite data also provide information on the variability in the intensity of precipitation [Indian Summer Monsoon (ISM) and Westerlies] in north Indian hills during the Late Holocene. The $\delta^{18}O$ values show strong variability between −2.1‰ and −8.9‰. The extremely high variability points to the monsoon from two different sources compared to other similar aged caves which are primarily controlled by one monsoon, such as the East Asian Summer Monsoon (EASM; although ISM has penetrated into some parts in the areas of EASM in the past) or the Westerlies. Therefore, we suggest that the Westerlies played an important role in the Late Holocene climate of the Indian Himalaya. As the source of the Westerlies is Mediterranean/Atlantic, the North Atlantic Oscillation (NAO) which was responsible for comparatively stronger Westerlies in southern Europe, may have brought higher precipitation to the north Indian hills. The stronger Westerlies may also have resulted in the highest precipitation between 0.5 and 0.25 ka BP (1450–1700 AD; a part of the LIA) in contrast to the weakening of the Indian Summer Monsoon (ISM) in peninsular India. The stalagmite has also recorded the driest period, peaking at ~3.2 ka BP which may be nearly synchronous with the final collapse of the Harappan culture in northwest India.

1. Introduction

The annual migration of the ITCZ (Intertropical Convergence Zone) and seasonal development of the monsoon winds are the key components of Indian climatology. In spring, the ITCZ migrates northward across the Indian Ocean and reaches its northernmost position during boreal summer. During the ISM period, a strong low-level monsoonal air flow is generated by a strong pressure gradient between the low-pressure cell over the Tibetan Plateau and a high-pressure cell over southern Indian Ocean. North of the equator, a strong southern-westerly air flow, known as the Somali or Findlater Jet (Findlater, 1996) transports large quantity of moisture, that is then released as monsoon precipitation over some parts of the southern Arabia and Indian subcontinent. Subsequently, the ITCZ jumps across a wide latitudinal range in a very short time and reaches its southernmost position. Therefore, the seasonal migration of the ITCZ strongly influences the onset, duration and termination of the rainy season in the tropics and subtropics and its structure further affects tropical and also extra tropical climate on a variety of time scales (ranging from monthly to millennial).

The Holocene climatic records from the tropical sites have revealed substantial changes in mean state hydrology (Congbin and Fletcher, 1988; Lau and Yang, 1997; An et al., 2000; Gasse, 2000; Maslin and Burns, 2000; deMenocal, 2001; Dykoski et al., 2005; Wang et al., 2005; Broccoli et al., 2006; Hu et al., 2008; Wanner et al., 2008; Yan et al., 2011). However, while the ISM core locations are primarily influenced by changes in the amount of precipitation, regions currently situated near the northernmost extension of the ITCZ most likely are also influenced by changes in the seasonality of monsoon precipitation (Fleitmann et al., 2003; Kotlia et al., 2012) due to shifts in the mean latitudinal position of the ITCZ. The ISM in summer and Westerlies (prevailing winds from Europe) in the winter are the two important atmospheric circulation patterns found in the Indian Central Himalaya (e.g., Benn and Owen, 1998). When the ISM is weakening, the Westerlies are

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strengthening and these influence the precipitation pattern. Unlike eastern and western Himalaya, the Central Himalaya receives precipitation due to the above mentioned monsoons, thus during the northern hemisphere winter when ITCZ descends, this part has different precipitation pattern based on the movement of the ITCZ and strength of the ISM (Mehta et al., 2012). The movement of mean position of the ITCZ to the Indian subcontinent and relatively sudden "onset" and "retreat" of the monsoon constitute a characteristic feature of the ISM (Goswami, 1998). The shortening of ISM season has a direct bearing on the gradual southward retreat of the mean summer ITCZ (Fleitmann et al., 2007). Variation in the latitude of ITCZ during the early and late Holocene also had an influence on centennial ISM rainfall (Bird et al., 2014). Because the variation in the mean latitudinal position of ITCZ influences tropical and extra tropical climate, the millennial-scale variations in the ISM strength and the past position of ITCZ are somewhat understood in one or other way (e.g., Neff et al., 2001; Fleitmann et al., 2007). However, the knowledge about high resolution decadal to centennial Holocene climate is limited especially in the central part of the Indian Himalaya (Phadtare, 2000; Rühland et al., 2006; Kotlia et al., 2012; Mehta et al., 2012; Sanwal et al., 2013) which is very sensitive to those changes.

Speleothems from monsoon core zone of India (see Fig. 1), as archives of past monsoon variation, have been studied by several workers (Yadava and Ramesh, 2001, 2005, 2006; Yadav et al., 2004; Sinha et al., 2007, 2011a, b; Lone et al., 2014). The speleothem research has also been carried out in nearby regions (Denniston et al., 2000; Laskar et al., 2011, 2013) as well as from Oman and Yemen (Neff et al., 2001; Burns et al., 2002; Fleitmann et al., 2003, 2007; Shakun et al., 2007) and China (Wang et al., 2001; Hou et al., 2003; Tan et al., 2003; Cai et al., 2006, 2012; Cheng et al., 2006, 2012; Zhou et al., 2009; Maher and Thompson, 2012; Shen et al., 2013;; Tan et al., 2013; Duan et al., 2014; Li et al., 2014a, b). In general, the Chinese stalagmites have been widely interpreted as a result of the amount of EASM rainfall (Maher and Thompson, 2012). However, some records have documented the influence of the ISM on $\delta^{18}O$ precipitation in some Chinese caves, e.g., Yangkou and Sanbao in mainland China (Li et al., 2014a, b), which has also been proved by the modeling studies (Pausata et al., 2011). It has been argued that the significant amount of moisture was originated in parts of China from the ISM during its higher intensity in the past (Cheng et al., 2012). On the other hand, the speleothems from the Peninsular India, particularly the monsoon core region are interpreted as a result of the sum of ISM (Yadav et al., 2004; Lone et al., 2014).

From Indian Himalaya, on the other hand, however, there is only one published speleothem record for the last deglacial period (Sinha et al., 2005) and to best of our knowledge, there are only two Himalayan records covering the last about 2 ka BP (Sanwal et al., 2013) and 400 years (Kotlia et al., 2012; Duan et al., 2013) respectively, both clearly showing the wet LIA. The observations of Kotlia et al. (2012) and Sanwal et al. (2013) correlate very well with a number of past studies in those regions influenced by both the ISM and Westerlies (e.g., Wu et al., 2004; Chen et al., 2010; Zhao et al., 2010) but differ from those areas which are entirely influenced by the ISM.

Considering this, we studied a cave speleothem from the Indian Central Himalaya (Fig. 1) with an aim to demonstrate a high-resolution scenario of palaeo-precipitation changes. Our work is primarily focused on (a) replacing the selection of poorly dated and inconsistent records (e.g., Chauhan et al., 2000; Phadtare, 2000; Ranhotra et al., 2001; Kar et al., 2002; Chakraborty et al., 2006; Rühland et al., 2006; Kotlia et al., 2010; Rawat et al., 2012; Kotlia and Joshi, 2013) with very well dated records and (b) producing multi-decadal high resolution climatic data from the Central Indian Himalaya. Relationship of climate variability with the mid latitude Westerlies from some parts of China are well documented (Pausata et al., 2011; Cheng et al., 2012; Li et al., 2014a, b). In the Indian Himalayan scenario, however, we observe that the importance of Westerlies has received much less attention than the ISM rainfall. Therefore, the magnitude and complexity of these tasks have highlighted the need for an effort aimed at generating, quantifying,

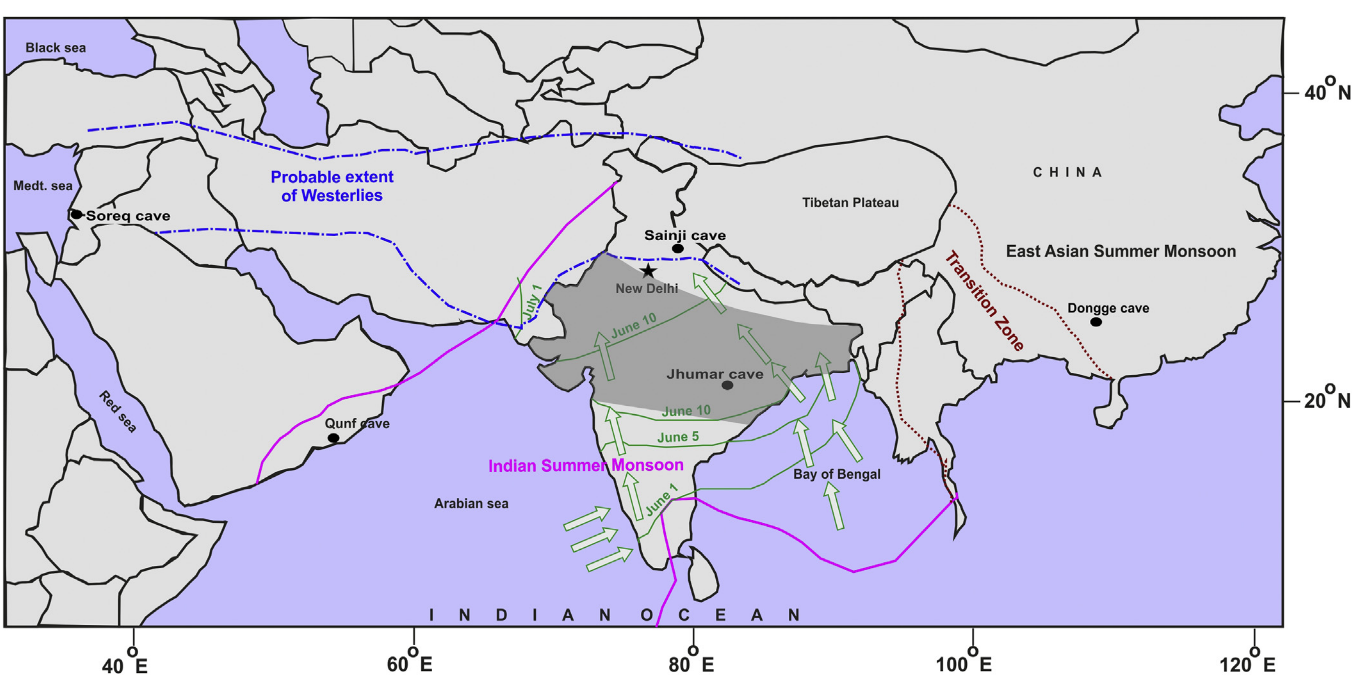

Fig. 1. Map showing sub-systems of monsoon (ISM, EASM and approximate extent of Westerlies; modified afterLi et al., 2014a, b) and mean annual arrival date of the ISM (lines with dates) and principal trajectories of moisture masses associated with monsoon (arrows). Dot is location of Sainji cave (SA-1) site (within the influence of ISM and Westerlies). Other caves influenced by different monsoons are also discussed in the text. Dark grey shaded area is core monsoon zone of India.