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Panigarh cave stalagmite evidence of climate change in the Indian Central Himalaya since AD 1256: Monsoon breaks and winter southern jet depressions

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ABSTRACT

Variations in petrography, stable isotopes, reflectance, and luminescence along the central growth axis of a 14.5 cm stalagmite from Panigarh cave indicate cooler and slightly wetter conditions in the Himalayan foothills of northern India during the Little Ice Age (LIA), which lasted from ~AD 1489–1889 based on deposition of calcite, and AD 1450–1820 based on rapid changes in $\delta^{18}O$ values. Conditions were warmer and drier during the preceding Medieval Climate Anomaly (MCA) and also in the post-LIA periods, as evidenced by deposition of aragonite. A review of currently existing stalagmite and other proxy data from south and east Asia reveals a broad spatial pattern in precipitation over south and east Asia during the LIA, with northern areas showing generally increased precipitation and southern areas reduced precipitation. During the MCA and after the LIA, the records suggest this pattern was reversed. Weaker ISM during the LIA brought drought conditions to the core ISM area but triggered more monsoon 'breaks' that brought higher precipitation to the Himalayas. At the same time, the weaker ISM may also have pushed more depressions along the path of the southern winter jet which brought more winter precipitation to the Himalayas and therefore a LIA wetter in our study area.

1. Introduction

The Indian Summer Monsoon (ISM) is crucial to the people of India and elsewhere in South Asia. Two-thirds of Indians depend on farm income and over 40% of the cropped area has no form of irrigation other than the rains. More than half of India's farm output comes from summer crops dependent on the ISM. For good crop production, the rains have to be not just robust but also evenly spread across states. The ISM also replenishes 81 nationally-monitored water reservoirs vital for drinking, power and irrigation (Haq and Choudhury, 2014). The health of the Asian Summer Monsoon (ASM) affects 60% of the Earth's population as it provides the water needed for agriculture and industry (Davis et al., 2005). It is therefore, important to understand how the ASM varies over time and the factors that are responsible for changes in its strength.

Although fickle today, the ISM may have been much weaker in the past for long periods of time, particularly during the Little Ice Age (LIA) and other cold intervals of the Holocene (Anderson et al., 2002, 2010; Gupta et al., 2003). A weaker monsoon should bring less precipitation across the Asian mainland. However, the data are ambiguous with much recent evidence suggesting wetter conditions during at least certain episodes of the LIA in Nepal (Denniston et al., 2000), northern India (Rühland et al., 2006; Kotlia et al., 2012, 2014; Duan et al., 2013; Sanwal et al., 2013), and southern China (Chu et al., 2002; Chen et al., 2005) as well as northwestern China (Chen et al., 2009). However, no high-magnitude flood deposits have been identified in the six large rivers crossing central and western India suggesting that there was no really intense

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precipitation at this time and in fact that the conditions were probably drier from the 14th to the 19th centuries (Kale and Baker, 2006). Looking at the ambiguous and uncertain data set, it is obvious that more information is needed to elucidate conditions during the LIA. This paper presents evidence from a stalagmite (PGH-1) from Panigarh cave near Pithoragarh in northern India, located in the southern foothills of the Himalayas. The stalagmite was active when collected in 2006 and preserves evidence of variations in the ISM during the past ~750 years, including the period of the LIA. Multi-proxy data from the stalagmite, including variations in stable isotopes, reflectance, U–V stimulated luminescence, and petrography, provide data on climate during the Medieval Climate Anomaly (MCA) and LIA in this area. Neither of these periods appears to have been synchronous across the globe. The MCA lasted from about AD 950 to 1250 (Mann et al., 2005) and the LIA from AD 1550–1850 with three cold intervals at ~AD 1650, 1770, and 1850 (NASA) or alternatively, from about AD 1350 to about 1850 (IPCC Fourth Assessment Report: Climate Change, 2007).

The climate of India is dominated by the ISM but has distinct warm and cold seasons. During winter the upper westerlies over Asia split into two currents, one north and the other south of the high Tibetan (Qinghai–Xizang) Plateau and re-join off the east coast of China. The two jet stream branches have been attributed to the disruptive effect of the topographic barrier to airflow. However, the stronger southern branch over northern India corresponds to a strong latitudinal thermal gradient (from November to April). Air subsiding beneath the upper westerly current gives dry outblowing northerly winds from the subtropical anticyclone over NW India and Pakistan. Surface winds are NW over most of northern India. Important is the steering of winter depressions over northern India by the upper jet. The lows, which are not usually frontal, appear to penetrate across the Middle East from the Mediterranean and are important sources of rainfall for northern India and Pakistan, especially as it falls when evaporation is at a minimum. It is significant that the mean axis of the winter jet stream over China shows a close correlation with the distribution of winter rainfall. In the rear of these depressions are invasions of very cold air. In fact, winter mean temperatures in less-protected southern China are much lower than in India (Barry and Chorley, 2003).

In early summer, generally during the last week in May, the southern branch of the high-level jet begins to break down, gradually shifting northward over the Tibetan Plateau. There is a variable pulse alternating between active and break periods during the May to September summer monsoon flow. During active periods the convective monsoon trough is located further north giving heavy rain over north and central India and the west coast. During break conditions, the Intertropical Convergence Zone (ITCZ) shifts to the south, the easterly jet weakens and subsiding air is forced to rise by the Himalayas along a break trough located above the foothills, which replaces the monsoon trough during break periods (e.g. Ramaswamy, 1962). This circulation brings rain to the Himalayan foothills and Brahmaputra valley at a time of generally low rainfall elsewhere. The shift of the ITCZ to the south is accompanied by a similar southward movement and strengthening of the westerly jet to the north weakening the Tibetan anticyclone. The lack of rain over much of the subcontinent during break periods may be due in part to the eastward extension across India of the subtropical high-pressure cell centered over Arabia at this time. During October the westerly jet re-establishes itself south of the Tibetan Plateau and cool season conditions are restored (Barry and Chorley, 2003).

2. Panigarh cave

Panigarh cave (29°33′10″ N; 80°07′03″ E; 1520 m amsl) is 300 km northeast of New Delhi, 30 km west of the western boundary of Nepal, and 1.5 km west of Boonga Village (Fig. 1). On January 6, 2006, an active, 14.5 cm long stalagmite (PGH-1) was collected from a 4 m long cave with an entrance of 1.4 m^2. The cave is developed in the Precambrian Thalkedar Limestone extending about 250 m above the cave with a surface cover of about 80 cm thick brown–black soil. The vegetation is largely C_3 being composed predominantly of *Pinusroxburghii* with small shrubs, grasses and herbs. The climate is subtropical monsoon with wet, warm summers and drier, cooler winters. Annual precipitation is 1260 mm, about 80% falling during the monsoon season from June to September. At Pithoragarh, 9 km NW of Panigarh cave, the mean annual temperature is 17.4 °C ranging from 7.7 °C in January to 23.6 °C in June (Kotlia et al., 2000, see Table 1).

3. Materials and methods

The PGH-1 stalagmite was cut along the central growth axis. After polishing, one of the exposed surfaces was scanned at 300 dpi spatial resolution and 8 bit (256 increments) gray level resolution. It was then illuminated by long-wave ultraviolet light (320–420 nm wavelength) from two Macken Instruments Model 22-UV lamps in a darkroom. Luminescence from the stalagmite was recorded by a Nikon D-70, 6-megapixel digital camera fitted with a Kodak Wratten Gelatin Filter #2E to prevent transmission of the UV excitation energy band. Variations in reflectance and luminescence were measured along a 10-pixel-wide traverse down the central growth axis of the stalagmite using image analysis software. Gray-level (0 = black; 255 = white) and luminescence (0 = black; 255 = white) values have a spatial resolution of 0.07 mm (i.e., ~0.6 year per dot).

Thin sections for petrographic study were prepared from the other half of the stalagmite. Five samples of ~100 mg were drilled at 6, 25, 70, 110, and 140 mm from the top of the stalagmite for ICP-MS U-series dating following procedures outlined in Edwards et al. (1987), Cheng et al. (2000), and Shen et al. (2002). Ages were calculated using half-lives listed in Cheng et al. (2000) and are reported with 2σ analytical errors.

Powdered material for stable isotope analysis was removed by drilling at intervals along the central growth axis of PGH-1. In the upper and lower aragonite sections of the stalagmite, samples of 50–100 μg were drilled at 1.5–2 mm intervals. Fourteen samples were processed at the Savannah River Ecology Laboratory, University of Georgia, on a Finnigan Deltaplus XL isotope ratio mass spectrometer operated in continuous flow mode (CF-IRMS) using a Gasbench II peripheral device (Jimenez-Lopez and Romanek, 2004), with analytical precision (1σ) ±0.14‰ for $\delta^{13}C$ and ±0.23‰ for $\delta^{18}O$, based on the repeated measurements of the NBS-19 standard. Another 27 samples were processed in the Department of Geology Stable Isotope Laboratory at the University of Alabama in Tuscaloosa on a Finnegan Deltaplus or Delta V isotope ratio mass spectrometer using a GasBench-IRMS system following methods discussed in Lambert and Aharon (2011). Reproducibility for both $\delta^{13}C$ and $\delta^{18}O$ was ±0.1‰ based on NBS-19 and sample repeats.

In the central section of PGH-1, which consists of variable portions of calcite and aragonite, 30samples of 10–20 mg were drilled at 2.5 mm intervals. These samples were first subjected to XRD analysis to establish percentage aragonite and percentage calcite; then $\delta^{13}C$ and $\delta^{18}O$ were determined on the very same samples in the University of Georgia, Department of Geology Stable Isotope Laboratory on a Finnegan Delta E ratio Mass Spectrometer with precision of 0.04‰ for $\delta^{13}C$ and 0.05‰ for $\delta^{18}O$ based on repeated measurements with the NBS-19 standard.

Aragonite is enriched in ^{13}C by 1.7‰ (Romanek et al., 1992) and in ^{18}O by 1.0‰ (Grossman and Ku, 1986) compared to calcite when deposited from water with the same $\delta^{18}O$ and $\delta^{13}C$ values. As the