ENVIRONMENTAL STUDIES

The Indian monsoon variability and civilization changes in the Indian subcontinent

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The vast Indo-Gangetic Plain in South Asia has been home to some of the world's oldest civilizations, whose fortunes ebbed and flowed with time—plausibly driven in part by shifts in the spatiotemporal patterns of the Indian summer monsoon rainfall. We use speleothem oxygen isotope records from North India to reconstruct the monsoon's variability on socially relevant time scales, allowing us to examine the history of civilization changes in the context of varying hydroclimatic conditions over the past 5700 years. Our data suggest that significant shifts in monsoon rainfall have occurred in concert with changes in the Northern Hemisphere temperatures and the discharges of the Himalayan rivers. The close temporal relationship between these large-scale hydroclimatic changes and the intervals marking the significant sociopolitical developments of the Indus Valley and Vedic civilizations suggests a plausible role of climate change in shaping the important chapters of the history of human civilization in the Indian subcontinent.

INTRODUCTION

The Indian summer monsoon (ISM) is a large land-ocean-atmosphere coupled system that transports substantial amounts of moisture during boreal summer across the Indian Ocean into the Indian subcontinent, reaching as far northwest as Pakistan and as far north as the southern Himalayas (Fig. 1) (*1*). The lives of billions of people in the Indian subcontinent are tightly intertwined with the vagaries of ISM rainfall to the extent that even modest changes in its spatiotemporal patterns can bring substantial socioeconomic hardship to the region (*2*, *3*).

The history of human civilizations in the north and northwestern parts of the Indian subcontinent—a semiarid region located at the periphery of the monsoon's belt—is rich in accounts of ecological, social, and cultural changes. These important societal changes include the expansion and deurbanization of the Indus Valley (Harappan) civilization (*4*–*9*) followed by the rise and fall of the Vedic civilization (*10*, *11*) and a dramatic collapse of the Tibetan Guge Kingdom in the 17th century AD (Fig. 1) (*12*, *13*). A series of mechanisms explaining the causes of these civilization and cultural changes have been proposed. These include climate change (*14*–*21*), disease (*22*), tectonic-induced shifts of river courses (*7*, *23*), and changes in crop patterns (*24*). Although several climate proxy records of the Holocene ISM variability [for example, (*14*–*17*, *20*, *21*, *25*, *26*)] have been used to examine relationships between climate and civilization change during the Holocene, the ISM variability—particularly on time scales of societal interest and its linkages with the civilization history—is poorly known [for example, (*5*, *8*, *9*, *27*)]. This is largely due to a lack of continuous high-resolution and precisely dated climate records, which precludes a reliable assessment of the relationship between hydroclimatic variability and archeological and historical accounts of civilization and cultural changes in the region.

The ISM reconstruction

Previously, we have reported a high-resolution and precisely dated speleothem oxygen isotope ($\delta^{18}O$) record over the last ~2000 years from Sahiya Cave, North India (*28*). Sahiya Cave (30°36′N, 77°52′E, ~1190 m above sea level) is located in the state of Uttarakhand, North India, ~200 km north of New Delhi. The study area lies between the Gangetic Plains and the Lesser Himalayas (Fig. 1). To a first order, the annual ISM precipitation cycle in this region is a manifestation of the seasonal migration of the intertropical convergence zone (ITCZ) (*1*, *2*), with ~80% of precipitation falling between the months of June and September with positive precipitation minus evaporation conditions occurring only during the summertime (*28*). The study area is located at the fringe of the ISM-influenced region, and thus, the oxygen isotope of precipitation ($\delta^{18}O_p$) in this region is strongly influenced by spatially integrated upstream changes in the ISM circulation dynamics and rainfall amounts (*28*–*30*).

We have previously shown that the contrasting patterns of subdecadal to decadal length intervals of strong and weak ISM circulation regimes produce distinct $\delta^{18}O_p$ signatures, which in turn are recorded by variations in the $\delta^{18}O$ of speleothems from the study area (*28*, *29*). Our proxy reconstructions of multidecadal oscillations and a marked declining trend in the ISM rainfall since the mid-20th century are in strong agreement with the instrumental observations. In addition, we have also shown that the Sahiya $\delta^{18}O$ record also exhibits decadal-multidecadal length episodes of high-amplitude ISM variability (for example, the ~1620–1630 AD event) that clearly fall outside the range of instrumental observations (*28*). Our record also demonstrates prominent multicentennial-scale variations in the ISM strength that closely follow the Northern Hemisphere (NH) temperature change. Here, we extend the Sahiya $\delta^{18}O$ record further back to 5700 yr BP (present, 1950 AD), enabling us to reliably assess the relationship between the ISM variability and civilization changes in the region.

The new Sahiya $\delta^{18}O$ record presented in this study consists of two stalagmite (SAH-2 and SAH-3) $\delta^{18}O$ profiles with a total of ~1440 $\delta^{18}O$ measurements and 32 ^{230}Th dates (figs. S1 and S2). By combining our previous Sahiya $\delta^{18}O$ record (*28*), we composited a high-resolution (average resolution, ~1.8 years) and well-dated ISM record, spanning the last 5700 years. Previous data (*28*, *29*) and well-replicated additional speleothem $\delta^{18}O$ profiles from this study (figs. S2 and S3) demonstrate that temporal changes in the Sahiya Cave $\delta^{18}O$ values reflect local changes in the $\delta^{18}O_p$ at the cave area, which in turn vary inversely with the large-scale variation in ISM rainfall (fig. S4) (*28*–*30*).

The composite Sahiya $\delta^{18}O$ record over the past 5700 years is characterized by a long-term decreasing trend in ISM, which occurred in

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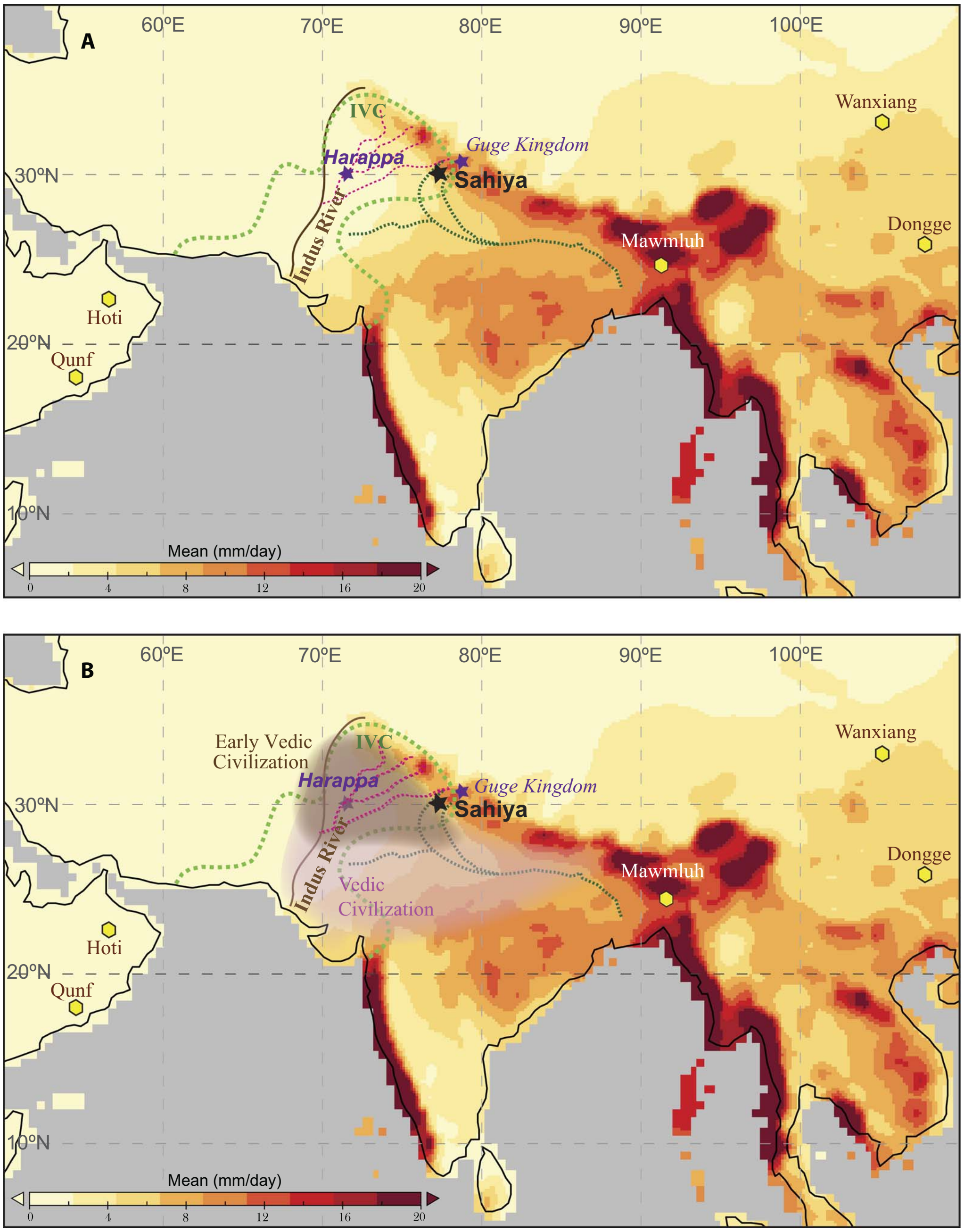

Fig. 1. Site locations and the spatial pattern of modern ISM precipitation. (**A**) The spatial extent of the Indus Valley Civilization [IVC; ~5300–3300 years before present (yr BP)] is marked by dotted green lines along with the Indus River (brown line). Shading indicates the spatial pattern of JJAS (June to September) rainfall rate (mm/day) from the gridded precipitation data set from the Global Precipitation Climatology Centre Monitoring Product v5 (*56*). The Sahiya Cave is shown by a black star. (**B**) Same as (A), except spatial extent of the Early (~3400–3050 yr BP) and Later (~3050–2450 yr BP) Vedic periods are shown. Hexagons depict other cave sites mentioned in the text.

tandem with the decreasing NH summer insolation (*30*) and a southward migration of the ITCZ (Fig. 2) (*31*). This long-term declining trend in ISM is broadly consistent with the ISM reconstructions inferred from other proxy records from the Arabian Sea region [for example, studies by Fleitmann et al. (*25*, *26*)] and with the East Asian speleothem records from China (Fig. 2) [for example, studies by Cheng *et al.* (*30*) and Wang *et al.* (*32*)]. In contrast, the structure of ISM finer-scale variability inferred from our record differs from other marine- and speleothem-based records of ISM, East Asian summer monsoon, and ITCZ, respectively. The multidecadal-to-centennial scale variability between our North Indian (*28*) and central-eastern Indian speleothem records (*3*) (Fig. 2) is apparently different, highlighting the spatial heterogeneities in ISM rainfall between the northern and the central/peninsular Indian subcontinent. In this regard, our North India Sahiya $\delta^{18}O$ record is uniquely suitable for assessing the societal changes in the northern portion of the Indian subcontinent.

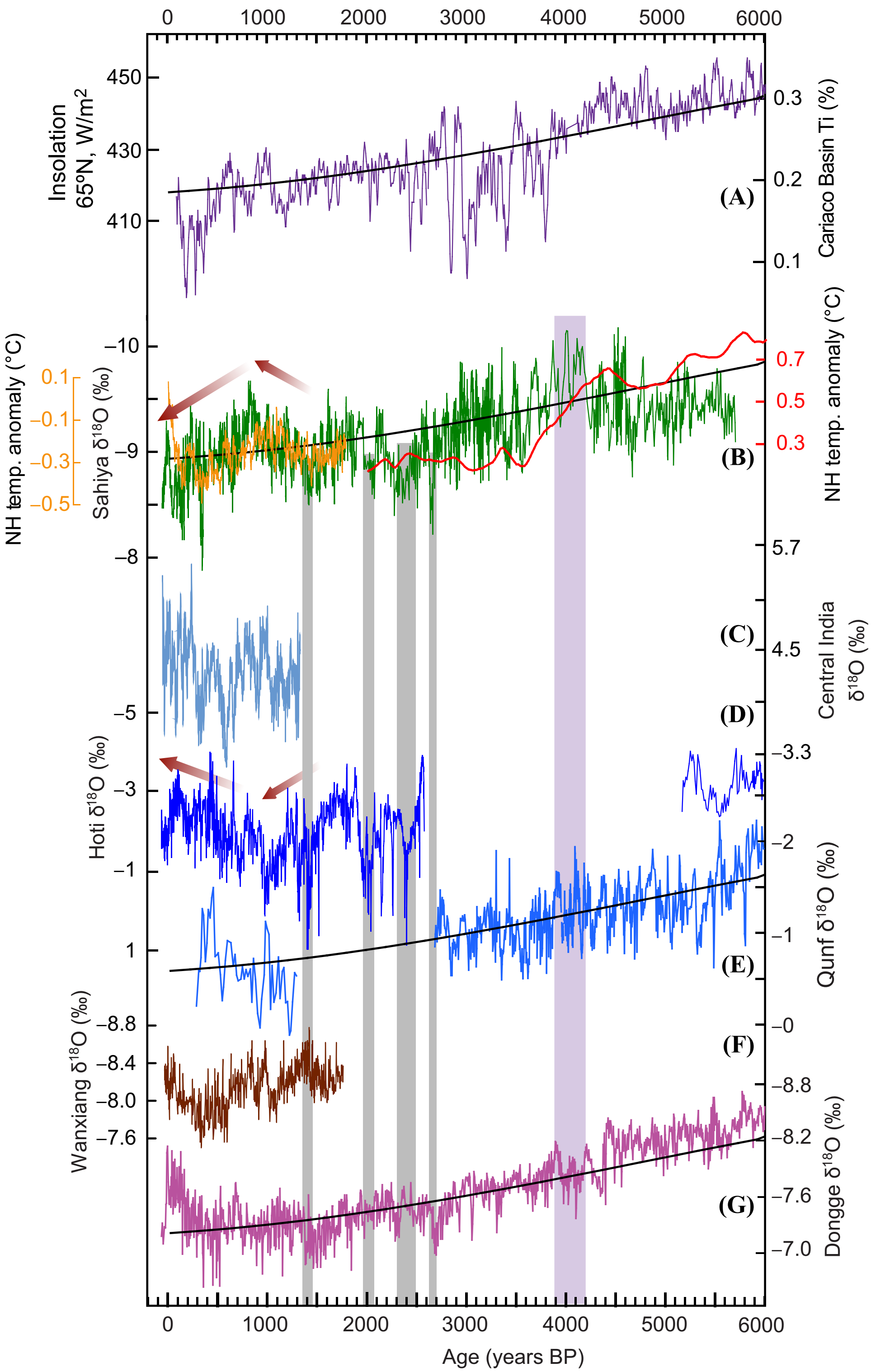

Fig. 2. Comparison of the Sahiya record with other climate records. (**A**) The Cariaco Basin titanium record (*31*), (**B**) the composite Sahiya $\delta^{18}O$ record (green this study), the NH temperature anomalies over the last 2000 years [orange (*57*)], the Holocene [red (*58*)], (**C**) the central India $\delta^{18}O$ record (*3*), and (**D**) the Hoti and (**E**) Qunf ISM records from Oman (*25*, *26*). (**F**) Wanxiang (*59*) and (**G**) Dongge (*32*) East Asian monsoon records from China. Black curves are 21 July insolations at 65°N (*60*). The arrows illustrate different trends between the Sahiya and Hoti records over the last ~1500 years. The 3900–4200 year event is shown with the purple bar. Gray bars show some centennial-decadal events in the ISM records.

The Indian monsoon and NH temperature

The composite Sahiya $\delta^{18}O$ record bears substantial similarities with NH temperature reconstructions (Fig. 2 and fig. S5). This covariance is particularly evident during the last two millennia, when the NH temperature reconstruction is more robust (*28*). The intervals with lower $\delta^{18}O$ values (stronger ISM) correspond with intervals of warmer periods observed in the NH temperature reconstruction such as ~800–1200, 1600–2300, 2900–3300, and 3800–4800 yr BP, which were associated with the Medieval Climate Anomaly (MCA), Roman Warm period (RWP), Minoan Warm period (MWP), and the late portion of the mid-Holocene Climate Optimum (HCO; Fig. 3) (*33*), respectively. Conversely, the heavier $\delta^{18}O$ excursions (weaker ISM intervals) coincide with cold periods such as the Little Ice Age (LIA), Dark Age Cold period (DACP), as well as other prominent cold times and events such as the pre-Roman Cold period (pRCP) (*34*) and a cold event during the RWP at ~2100 yr BP (Fig. 3) (*35*, *36*).

The observed coupling between the ISM and NH temperature on centennial time scales is not surprising because the monsoon is essentially a phenomenon of seasonal atmospheric circulation reversal, which is thermally driven via land-sea temperature contrast (*37*). Furthermore, a close linkage has been proposed between the westerly jet position and the ISM intensity on the millennial to seasonal time scales [for example, studies by Schiemann *et al.* (*38*) Chiang *et al.* (*39*), and Cheng *et al.* (*40*)]. Given that the westerly jet position is effectively related to the meridional temperature gradient across the Eurasian continent, the large-scale temperature changes over the NH can modulate the temperature gradient and, in turn, the westerly jet position and, consequently, the ISM variations. The Himalayan glacial meltwaters contribute significantly

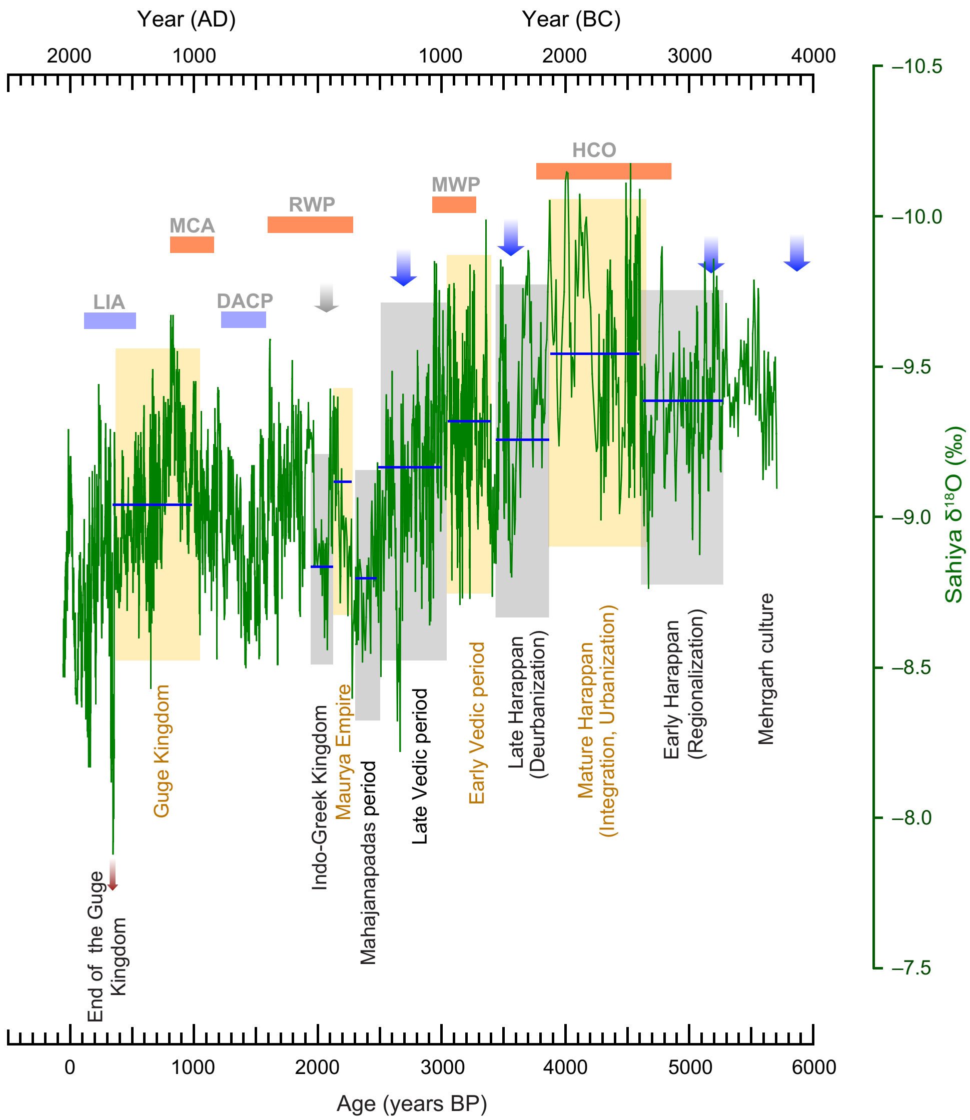

Fig. 3. The Sahiya $\delta^{18}O$ record in comparison with NH temperature and the civilization and cultural history in the northwestern Indian subcontinent. Orange bars indicate the temporal range of warm climate periods: the MCA, DACP, RWP, and MWP and the later part of the mid-HCO (*33*). Blue bars indicate the cold climate events: the LIA, a cold event within the RWP (gray arrow) (*35*, *36*), and the pRCP (blue arrows) (*34*). The vertical shaded bars depict different civilization and culture periods, as labeled at the bottom. Horizontal blue lines mark the mean $\delta^{18}O$ values for each vertical bar.

to river flows in the northwestern Indian subcontinent, for example, near 45% for the modern Indus River (*41*), and thus, the covariance between the NH temperature and the ISM can influence the hydrological condition in the region concurrently via changing the ISM rainfall and via changes in the discharges of the glacial-fed Himalayan rivers, presumably because changes in the regional temperature should correlate broadly with the NH temperature.

The Indian monsoon and cultural changes

The IVC (ca. 5300–3300 yr BP) was one of the earliest three Bronze Age civilizations of the Old World (*4–9*), located in the northwestern portion of the Indo-Gangetic Plain, extending from what today is northeast Afghanistan to Pakistan and northwestern India (Fig. 1A). The IVC evolved from the Early Regionalization Phase (~5300–4550 yr BP) marked by agrarian-based communities into large urban centers between ~4550 and 3850 yr BP—the so-called Mature Phase. Between ~3850 and 3300 yr BP, an interval often referred to as the Deurbanization Phase, the total settled area and settlement sizes declined, many sites were abandoned, and a significant shift in site numbers and density was recorded toward the east (for example, *5*, *6*). The hydroclimate conditions during the evolution and subsequent decline of the IVC have remained a subject of debate (for example, *9*, *14–19*). On the basis of the Sahiya $\delta^{18}O$ record, the Early and Mature Phases occurred during a fairly wet/warm and climatically stable period. The Mature Phase began around an abrupt intensification of the ISM at ~4550 yr BP (Fig. 3) and sustained for nearly ~700 years to ~3850 yr BP, corresponding with the late portion of the mid-Holocene Climate Optimum, during which the ISM reached its maximum over the past 5700 years. It is plausible that the optimum (warm/wet) climate might have allowed the civilization to develop a farming system with large and reliant agricultural surpluses, which in turn supports the development of cities.

Previous studies have attributed societal collapses in the Middle East and in the Indus Valley to a climate event, the so-called "4.2 ka BP event" (or ca. ~4.2–3.9 ka BP event) (*15–21*, *42–45*). The 4.2 ka BP event in the Sahiya $\delta^{18}O$ record manifests as an interval of declining ISM strength, marked by a relatively higher-amplitude $\delta^{18}O$ variability and a slow speleothem growth rate, rather than as a singular prominent abrupt event (Fig. 2). A lack of an abrupt change in our record around the time is consistent with the idea that the 4.2 ka event did not influence the Deurbanization Phase (*14*) in contrast to the more severe societal impact it had on the Old Kingdom in Egypt and the Akkadian Empire in Mesopotamia (*42–45*).

As inferred from the Sahiya $\delta^{18}O$ record, a multicentennial trend to drier and possibly cooler conditions in the Indus Valley region started around ~4100 years ago (Fig. 3), coinciding with a considerable decrease in NH temperature and with the IVC Deurbanization Phase (~3850–3300 yr BP) (Fig. 2). In addition, some studies suggest reduced river flows in the region around this time (*46*, *47*). The reduced river flow reconstructions are broadly consistent with the pollen-based evidence of weak ISM in the region (*48*). Therefore, we surmise that reduced ISM and reduced meltwater discharge from the Himalayas, presumably due to colder temperatures and/or reduced westerly induced precipitation, were responsible for producing multicentennial-scale drier conditions that may have contributed to the Indus Valley deurbanization. This notion is consistent with an observed shift in the crop patterns (*24*), suggesting that reduced monsoon rainfall might have forced the residents to migrate toward the Ganges Basin in the east, where they established smaller villages and isolated farms (*6*, *47*). Together, the aforementioned observations suggest that the three phases of the IVC may be ascribed to the distinct alternating hydroclimatic pattern of the cold/dry-warm/wet-cold/dry (Fig. 3), rather than resulting from a singular dry event in the ISM.

Following the IVC Deurbanization Phase, the Indo-Aryans migrated into the Indus Valley at ~3400 yr BP, marking the beginning of the Vedic period (*49*, *50*) in the Indian subcontinent. Notably, the Early Vedic period (as attested in the Rigveda hymns) was marked by tribal or pastoral societies, centered in the northern Indus Valley (*10*, *11*). In the Sahiya $\delta^{18}O$ record, the Early Vedic period (~3400–3050 yr BP) was primarily characterized by relatively stable NH temperatures and stronger ISM (Fig. 3). The Vedic civilization spread to the east into the Gangetic Plain during a weak ISM event at ~3100 yr BP (Fig. 3). The transition of the Vedic society from a seminomadic life to a settled agriculture occurred near the end of this period, when the ISM intensified yet again (Fig. 3).

The Later Vedic period (as attested in the post-Rigvedic texts) between ~3050 and 2450 yr BP was a time when agriculture, metal, commodity production, and trade largely expanded (*50*). The Vedic era texts, which are important to the later Hindu culture, were also ultimately composed during this period. This period was marked by stable ISM and NH temperature, except for a decadal-scale weak ISM event centered at ~2660 yr BP (Fig. 3). The end of the Vedic period (~2450 yr BP) was marked by linguistic, cultural, and political changes and eastward migrations (Fig. 1B) (*4*, *10*), coinciding with an abrupt weakening of the ISM as inferred from our Sahiya $\delta^{18}O$ record (Fig. 3).

After the end of the Later Vedic period, a number of disparate political units in the Indian subcontinent coalesced into large kingdoms, referred to as the Mahajanapadas period (~2500–2272 yr BP) (*50*). This period was marked by frequent wars among 16 kingdoms and occurred within a rather weak ISM interval, as indicated by the Sahiya $\delta^{18}O$ record (Fig. 3). The Mahajanapadas period gave way to the Maurya Empire—the first unified and strong Kingdom—which endured from 2272 to 2135 yr BP at a time of relatively strong ISM (Fig. 3). The collapse of the Maurya Empire (*51*) also coincided with an abrupt weakening of the ISM at ~2135 yr BP (Fig. 3).

In addition to providing the hydroclimatic context to the aforementioned civilization changes in the Indo-Gangetic Plain, our Sahiya Cave $\delta^{18}O$ record also provides intriguing evidence for a possible role of climate change in contributing to the collapse of the Guge Kingdom in western Tibet at ~1620 AD. The Guge Kingdom emerged in the middle of the 10th century during the MCA and flourished over the most of its epoch (see Fig. 4 and Supplementary Text) (*12*, *13*). The sudden collapse of the Guge Kingdom in western Tibet, ~150 km northeast of Sahiya Cave (Fig. 1), has generally been attributed to military conflicts (see Supplementary Text). Today, this region is arid with a mean annual precipitation of less than 200 mm, which is derived mainly from the ISM (~80%). The aridity of the regions is due to its elevation (~3700 m), and its fringe location with respect to the ISM allows only a small fraction of the ISM moisture to reach this area. The collapse of the Guge Kingdom coincides with the most severe dry event in our record between ~1593 and 1623 AD (±20 years), when the ISM reached its minimum in the last 5700 years (contemporary with NH temperature minimum). This event apparently also coincided with widespread droughts and famines in North India (*52*).

CONCLUSIONS

The chronologically well-constrained Sahiya Cave $\delta^{18}O$ record, thus far the highest-resolution proxy record of ISM from the heart of the Indian

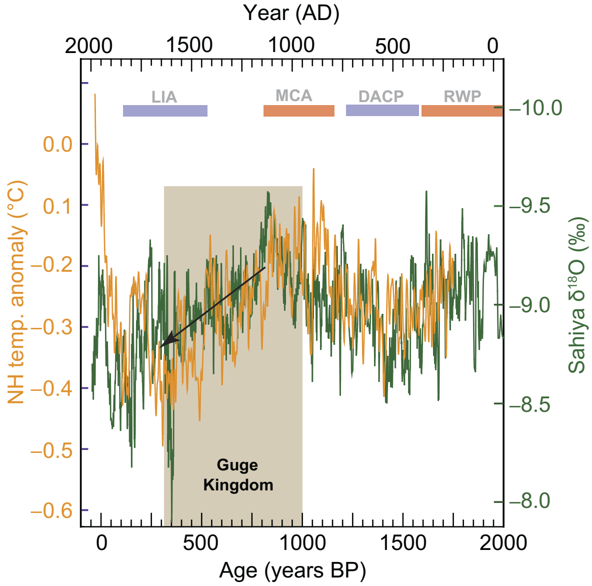

Fig. 4. The Sahiya $\delta^{18}O$ record over the last two millennia. Green and orange curves are the Sahiya $\delta^{18}O$ record (*28*) and the NH temperature anomaly reconstruction (*57*), respectively. The horizontal bars show the time range of warm (MCA and RWP) and cold (LIA and DACP) periods. The black arrow depicts a decreasing trend in both the NH temperature and the ISM during the Guge Kingdom epoch (the vertical bar). The collapse of the Guge Kingdom coincides with the weakest ISM over the last 5700 years.

subcontinent, provides a continuous history of the subcontinent-wide changes in the ISM rainfall over the last 5700 years. Our record, together with the available proxy reconstructions of NH temperature and ISM from the region, provides a broad hydroclimate context against which the civilization and cultural history of the Indian subcontinent can be assessed. Although our results clearly suggest a plausible role of climate change in shaping the course of civilization changes in the Indian subcontinent, undoubtedly there must also exist a range of local/regional climatic and anthropogenic factors that contributed to the past societal changes. A critical evaluation of the climate-culture link at these scales can only be achieved through comprehensive and coordinated assessments of the archeological and paleoclimate data.

MATERIALS AND METHODS

The Sahiya $\delta^{18}O$ record presented in this work was concatenated by using previously published $\delta^{18}O$ data from stalagmites SAH-B and SAH-A (*28*) together with new $\delta^{18}O$ data from three additional speleothems (SAH-2, SAH-3, and SAH-6). In the portions where the $\delta^{18}O$ profiles from different Sahiya Cave speleothems overlapped, the higher-resolution and better-dated profiles were retained for the composite record (fig. S2). To test the regional significance of the Sahiya $\delta^{18}O$ record, we developed a coarse $\delta^{18}O$ (~5-year resolution) record (ca. 2.0 to 5.5 ka BP) from the Mawmluh Cave from northeast India. The long-term centennial trends and even multidecadal variability among the two $\delta^{18}O$ records replicate remarkably well (fig. S3). The broad replications between the different stalagmite $\delta^{18}O$ records from the same cave during the contemporary growth periods, as well as between caves from two different regions, suggest that depositions of stalagmite calcite in the Sahiya Cave is occurring at or near the isotopic equilibrium. The chronologic framework of the stalagmites SAH-2 (26.6 cm), SAH-3 (7.6 cm), and SAH-6 (~10.5 cm) is established by 22, 10, and 11 ^{230}Th dates, respectively. Age models were established by using the COPRA (Constructing Proxy Records from Age model) algorithm (fig. S1) (*53*). We generated 2000 realizations of each age model to account for the dating uncertainties (2.5 and 97.5% quantile confidence limits).

^{230}Th dating method

The ^{230}Th dating was performed at the Isotope Laboratory, Xi'an Jiaotong University, using multicollector inductively coupled plasma mass spectrometers (Thermo Finnigan Neptune Plus). We use standard chemistry procedures to separate uranium and thorium for dating (*54*). A triple-spike (^{229}Th–^{233}U–^{236}U) isotope dilution method was used to correct for instrumental fractionation and determine U/Th isotopic ratios and concentrations. The instrumentation, standardization, and half-lives are reported in the study by Cheng *et al.* (*55*). All U/Th isotopes were measured on a MasCom multiplier behind the retarding potential quadrupole in a peak-jumping mode. We followed similar procedures of characterizing the multiplier as described in the study by Cheng *et al.* (*55*). Uncertainties in the U/Th isotopic data were calculated offline at the 2σ level, including corrections for blanks, multiplier dark noise, abundance sensitivity, and contents of the same nuclides in spike solution. Corrected ^{230}Th ages assume the initial $^{230}Th/^{232}Th$ atomic ratio of $4.4 \pm 2.2 \times 10^{-6}$, the values for a material at secular equilibrium with the bulk earth $^{232}Th/^{238}U$ value of 3.8. The U decay constants are reported in the study by Cheng *et al.* *55*. We obtained 43 ^{230}Th dates (table S1). The ages are in stratigraphic order within uncertainties.

Stable isotope measurements

Oxygen isotopic compositions of the stalagmites were analyzed at the Isotope Laboratory, Xi'an Jiaotong University, Xi'an, China. A total of ~1679 samples from the Sahiya speleothems and ~300 samples from the Mawmluh Cave (ML 15.1) were measured using a Finnigan MAT 253 mass spectrometer coupled with an on-line carbonate preparation system (Kiel IV). Results are reported in per mil (‰), relative to the Vienna Pee Dee Belemnite standard. Duplicate measurements of standards NBS19 and TTB1 show a long-term reproducibility of ~0.1‰ (1σ) or better. All Sahiya $\delta^{18}O$ data are listed in table S2.

Statistical analysis

The correlation coefficients between the instrumental data and the Sahiya record and between the NH temperature anomaly and the Sahiya record were obtained using the bootstrap resampling method. The sample size of each resampling is 30. The total resampling performance is 2000, which provides a significance level of $P < 0.05$ for a conservative estimate of the range of correlation coefficient. The results of statistical analyses are shown in figs. S4 and S5.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/3/12/e1701296/DC1

Supplementary Text

fig. S1. Age models of stalagmites.

fig. S2. New Sahiya $\delta^{18}O$ records between 5700 and 2000 yr BP.

fig. S3. Comparision of the Sahiya $\delta^{18}O$ record with the Mawmluh $\delta^{18}O$ record.

fig. S4. Comparison of the Sahiya $\delta^{18}O$ record with instrumental precipitation records in the cave area.

fig. S5. Comparison of the Sahiya $\delta^{18}O$ record with the proxy NH temperature reconstruction.

table S1. The composite Sahiya Cave oxygen isotope record.
table S2. ^{230}Th dating results.

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