An Abrupt Shift in the Indian Monsoon 4000 Years Ago

M. Berkelhammer,[1] A. Sinha,[2] L. Stott,[3] H. Cheng,[4,5] F. S. R. Pausata,[6,7,8] and K. Yoshimura[9,10]

The emergence of high-resolution proxy records from the Asian monsoon region suggests that the monsoon system is bistable and can abruptly transition between a suppressed and active state. This observation is critical in considering how the monsoon system may have influenced the development of societies across South and East Asia during the Holocene. Using a new high-resolution (~5 years/sample) speleothem stable isotope record from northeast India that spans the early and mid-Holocene, a number of abrupt changes in the oxygen isotopic composition of precipitation ($\delta^{18}O_p$) are documented. The most dramatic of these events occurred ~4000 years ago when, over the course of approximately a decade, isotopic values abruptly rose above any seen during the early to mid-Holocene and remained at this anomalous state for almost two centuries. This event occurs nearly synchronously with climatic changes documented in a number of proxy records across North Africa, the Middle East, the Tibetan Plateau, southern Europe, and North America. We hypothesize that the excursion could represent a shift toward an earlier Indian Summer Monsoon withdrawal or a general decline in the total amount of monsoon precipitation. The new record provides a very significant advance with respect to age control and sample resolution of terrestrial climate change over South Asia during this period when a number of major societal changes occurred. While evidence of a causal relationship between climate and the reorganization of the Indus Valley and Old Kingdom Nile civilizations is beyond the scope of this study, the tight age constraints of the record show with a high degree of certainty that much of the documented deurbanization of the Indus Valley at 3.9 kyr B.P. occurred after multiple decades of a shift in the monsoon's character but before the monsoon returned to its previous mid-Holocene state.

[1]Department of Atmospheric and Oceanic Sciences and Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, Colorado, USA.

[2]Department of Earth Sciences, California State University, Dominguez Hills, Carson, California, USA.

[3]Department of Earth Sciences, University of Southern California, Los Angeles, California, USA.

Climates, Landscapes, and Civilizations
Geophysical Monograph Series 198

10.1029/2012GM001207

[4]Institute of Global Environmental Change, Xian Jiaotong University, Shanghai, China.

[5]Department of Earth Sciences, University of Minnesota, Minneapolis, Minnesota, USA.

[6]Bjerknes Center for Climate Research, Bergen, Norway.

[7]Geophysical Institute, University of Bergen, Bergen, Norway.

[8]Joint Research Centre, Institute for Environment and Sustainability, European Commission, Ispra, Italy.

[9]Atmosphere and Ocean Research Institute, University of Tokyo, Tokyo, Japan.

[10]Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California, USA.

1. INTRODUCTION

Indian Summer Monsoon (ISM) precipitation during the twentieth century is characterized by a biennial oscillation, such that ISM precipitation varied between singularly strong and weak years but rarely deviated far from its mean state for consecutive years [*Meehl and Arblaster*, 2002]. This observation has engendered a hypothesis that dynamic feedbacks internal to the monsoon system ballasts it against sustained anomalies. *Meehl* [1993] and *Loschnigg and Webster* [2000] argue that the Indian Ocean (IO) provides the inertia to carry the influence of 1 year's monsoon circulation on to the next. According to this hypothesis, warm ocean temperatures in the IO are conducive to enhanced convection, which through air-sea interactions and large-scale wind fields during strong monsoon circulation, cool the surface ocean and ultimately suppress convection the following year.

The development of high-resolution paleoclimatic records from regions in the heart of the monsoon domain provide a long-term perspective on monsoon precipitation variability [*Buckley et al.*, 2007; *Sinha et al.*, 2011a; *Buckley et al.*, 2010; *Cook et al.*, 2010; *Borgaonkar et al.*, 2010; *Sano et al.*, 2009], which allows for an empirical test of the theory that the ISM is a self-regulating system. These proxy records from the monsoon region, which expand in many cases through the last millennium, clearly show the presence of monsoon anomalies that may last for decades or longer [*Buckley et al.*, 2010; *Cook et al.*, 2010; *Sinha et al.*, 2011a]. The most pronounced and best replicated of these events occurred during the mid- to late fourteenth century when monsoon precipitation was reduced to 80% of its mean for over 30 years [*Berkelhammer et al.*, 2010]. *Levermann et al.* [2009] and *Schewe et al.* [2011] use a simple dynamical model to show the capacity for the monsoon system to bifurcate between an active and suppressed state due to feedbacks between moisture advection and latent heating from condensation during monsoon precipitation. Based on this model, sustained monsoon suppression, as observed in the paleorecord, arises from the influence that external boundary conditions such as radiative forcing or low-frequency large-scale ocean modes have on IO sea surface temperatures (SSTs). These changes in SSTs influence the moisture-carrying capacity of the marine atmosphere and reduce moisture advection onto the Indian subcontinent during monsoon circulation. In a paleoclimate context, these changes appear large enough to override the internal stability that occurs from the quasi-biennial monsoon feedback cycle [i.e., *Meehl*, 1993].

The capacity for the system to bifurcate into a suppressed state is a source of prevailing concern in light of the consequences this would impose on municipal and agricultural systems across the Indian subcontinent. Paleoclimatic records of previous monsoon failures are therefore useful both for testing the dynamics of monsoon suppression and also for understanding the role that climate and water availability played in previous societal changes across Asia [*Graham et al.*, 2011; *Pausata et al.*, 2011; *Zhang et al.*, 2008; *Sinha et al.*, 2007]. For example, evidence of widespread famine and societal unrest across India during the major droughts of the fourteenth and seventeenth centuries illustrates the cultural impacts of such shifts in the monsoon system [*Sinha et al.*, 2007] and also provides a test of the capacity for hindcast general circulation model simulations to capture the dynamics of monsoon change [*Graham et al.*, 2011].

In this paper, we present a new record of the $\delta^{18}O$ of calcite from a speleothem that spans 3600 to 12,500 years B.P. The proxy is located in Cherrapunji, India, which is among the wettest locations on Earth with an annual average precipitation in excess of 11,000 mm, 70% of which falls during the summer monsoon months (June through September) [*Murata et al.*, 2007]. While the site is not located in the core monsoon zone of India [*Hoyos and Webster*, 2007], it is situated in a location that is highly sensitive to the northward propagating convective systems that originate in the Bay of Bengal and penetrate into the Tibetan Plateau. The record provides one of the first high-resolution terrestrial-based proxies of the monsoon over South Asia through the early to mid-Holocene and, therefore, yields opportunities both to capture the response of the monsoon to shifts in large-scale boundary conditions and to consider how the monsoon system influenced the spatiotemporal development of civilization across the Indian subcontinent. In the context of this multimillennia record, we focus our analysis and discussion on the presence of a singular abrupt and sustained change in the monsoon that occurred approximately 4000 years B.P. and lasted for almost two centuries (Figure 1).

The monsoonal shift documented here occurs temporally close to the *4.2k Event*, which was characterized by a series of abrupt and nearly concomitant climatological changes that occurred in the Middle East [*Weiss et al.*, 1993; *Cullen et al.*, 2000], and nearly synchronous with large hydrological changes in East Africa [*Gasse*, 2000; *Thompson et al.*, 2002; *Arz et al.*, 2006], southern Europe [*Drysdale et al.*, 2006; *Wagner et al.*, 2009], and southern China [*Hong et al.*, 2003] as well as in the tropical IO [*Rijsdijk et al.*, 2011]. There exists a standing controversy regarding the role that changes in the monsoon at this time may have played in the large-scale deurbanization of the Indus Valley Civilization that occupied a region presently part of northwest India and Pakistan [*Madella and Fuller*, 2006; *Misra*, 1984; *Clift et al.*, 2012]. A clear linkage between a shift in either the strength of the monsoon or winter season precipitation regimes and the documented societal changes at the time have long been

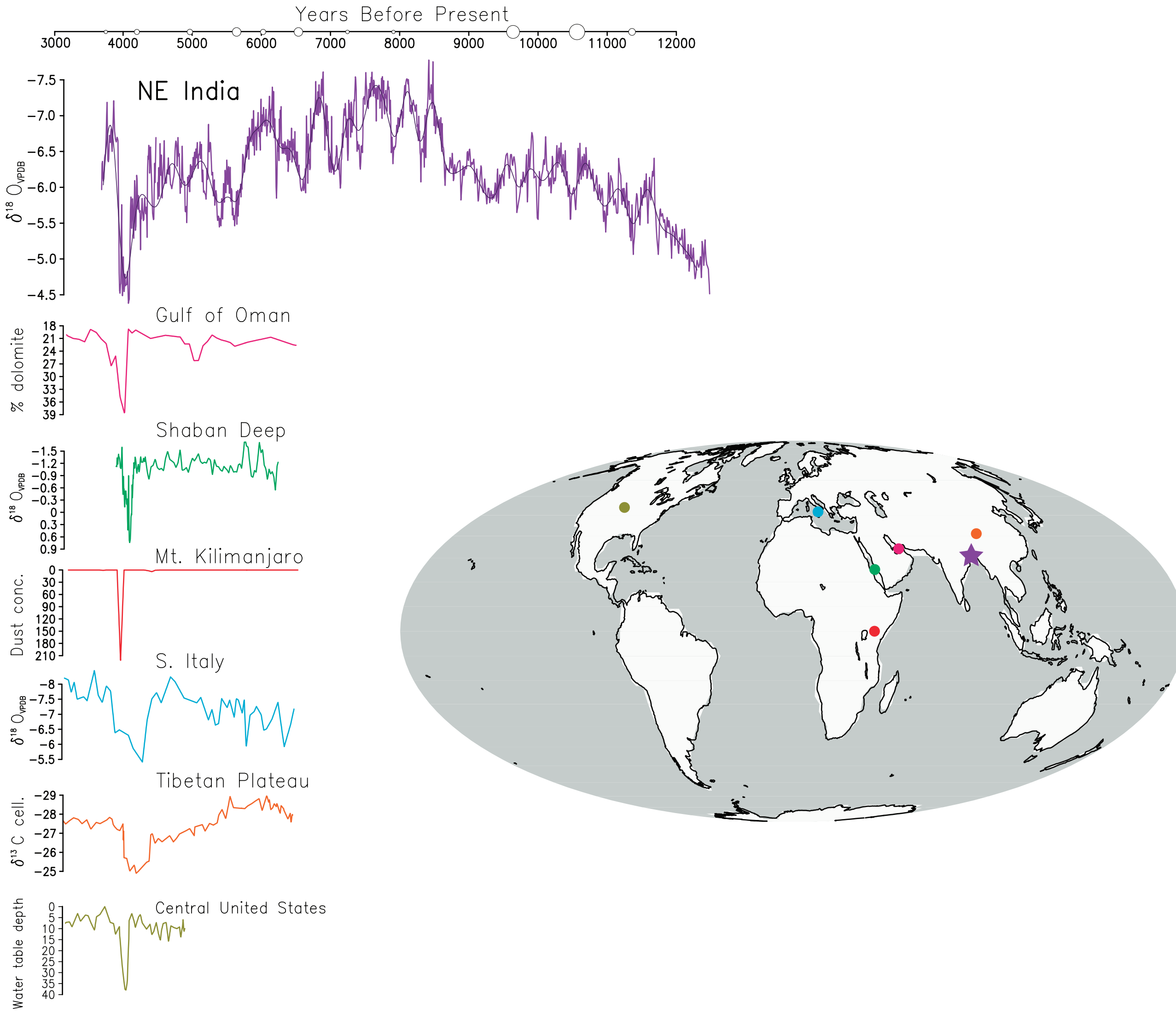

Figure 1. The KM-A isotope record from NE Indian is shown both as raw data (purple) and smoothed using a Lanczos filter (black) where the isotopic ratios are reported relative to Vienna PeeDee Belemnite and the *y* axis is reversed. Dots on the *x* axis are used to delineate the locations where U/Th dates were used to generate the age model. The size of the dot is proportional to the uncertainty. Please see Table 1 of supplementary material and Figure 2 for additional information on the dates. The location of the record is marked on the map as a star. A stack of additional records whose locations are represented with color coding on the map are shown for comparison. (top to bottom) Gulf of Oman dolomite record [*Cullen et al.*, 2000], the Shabban Deep foraminifera record [*Arz et al.*, 2006], the Mount Kilimanjaro dust record [*Thompson et al.*, 2002], southern Italy speleothem record [*Drysdale et al.*, 2006], Tibetan Plateau $\delta^{13}C$ sedimentary cellulose [*Hong et al.*, 2003], and lake level record from central United States [*Booth et al.*, 2005].

hampered by (1) poor age constraints on many of the regional proxy records [*Singh et al.*, 1990; *Enzel et al.*, 1999] and (2) that many of the proxies such as lake pollen or sedimentation rates may be influenced by nonclimatic factors such as tectonics or land use change [*Madella and Fuller*, 2006; *Clift et al.*, 2012]. Further adding to the enigma is the fact that some key regional proxies show no obvious evidence for climatic changes during this period [*Fleitmann et al.*, 2003]. We aim to shed light on this controversy by providing a direct terrestrial climate proxy from the Indian subcontinent, which has unprecedented age constraints (20 years) and resolution (5 years) during the period in which significant deurbanization occurred. The new record presented here suggests that the period of large-scale Indus Valley deurbanization [*Madella and Fuller*, 2006] occurred while the Indian Monsoon system was experiencing an anomaly larger than any other during the early to mid-Holocene.

2. METHODS

2.1. Analytical Analysis

In 2005, a calcitic stalagmite (KM-A) was collected from Mawmluh Cave (25°15′44″N, 91°52′54″E, elevation 1290 m) located in Cherrapunji, Meghalaya, in northeast India. KM-A was collected from a large chamber of the cave about 1500 m from the entrance. Continuous temperature measurements over the course of a year from inside the chamber suggest a remarkably stable ambient environment with temperatures varying between 18.0°C and 18.5°C [*Breitenbach*, 2009]. Repeated spot measurements of the relative humidity showed values in excess of 95% even during the dry season. High relative humidity, minimal temperature fluctuations, and the deep location of the sampling spot represent theoretically optimal conditions for calcite to form in isotopic equilibrium with the percolating precipitation. While no mineralogical analyses were done on the sample, there were no obvious visual changes in the color or texture during the 4 kyr B.P. excursion. Furthermore, because this region is among the wettest locations on Earth and has experienced only minimal interannual variations during the instrumental period, we have confidence that the vapor pressure in the chamber would remain close to saturated even during periods when the monsoon was relatively weak. This suggests that variations in the $\delta^{18}O$ of the calcite reflect, to a first order, changes in the precipitation-weighted $\delta^{18}O_p$.

The sample was split along its growth axis, and continuous powdered calcite samples were removed using both a Dremel tool and automated drilling system. The isotopic composition of individual powdered calcite samples was measured using dual-inlet isotope ratio mass spectrometry, where the calcite is reacted with phosphoric acid, and the resulting CO_2 is measured relative to a reference gas that has been calibrated against a series of known isotopic standards. The analyses were performed using an online automated carbonate preparation system linked to a VG Prism II isotope ratio mass spectrometer housed at the University of Southern California's stable isotope lab. Repeat measurements of standards and samples reveal a procedural uncertainty of <0.15‰. A total of 1128 isotopic measurements were made principally during 2009. The samples spanning the 3.8 to 4.5 kyr B.P. period were rerun on the same instrument in 2011 to ensure the analytical uncertainty during this critical period of the record were representative of the system's typical behavior.

2.2. Age Model

The age-depth relationship along the sample was constrained with 12 U/Th dates measured at the University of Minnesota following the methods of *Cheng et al.* [2009] (see Table 1) (refer to Appendix A for details of supplementary material). The age model was developed using the approach described by *Scholz and Hoffmann* [2011], where a linear interpolation between depth and age is made through each progressive triplet of adjacent U/Th dates (Figure 2). This process is repeated for 10,000 iterations using the two-sigma uncertainty of the U/Th date as constraints in "jigging" the age model. This procedure affords a quantitative method to continuously assess the age uncertainty along the record despite having analytical constraints only at locations where the U/Th dates exist. Furthermore, this iterative procedure minimizes the influence imparted on the age model by subjective decisions regarding the depths U/Th measurements are made.

Although the full data set from KM-A is presented in Figure 1, we focus the discussion primarily on the time period between 3800 and 5500 B.P. when the largest singular event is observed. During this period, the age uncertainty is <30 years, and the record shows linear growth rates, providing confidence in the timing (onset and duration) of the event. We emphasize that due to large age uncertainty and a rapid change in the growth rate during the middle part of this record (i.e., ~6–12 kyr B.P., Figure 2), this section is presented only preliminarily until additional constraints on the ages are available. While the growth rate obtained from the age-depth relationship could also be used as an additional

Table 1. U/Th Dates Used to Develop the KM-A Age Model Following the Analytical Methods of *Cheng et al.* [2009][a]

Depth (mm)	Age (B.P.)	Error
0	**3,654**	**20**
6	**4,112**	**30**
29	**5,084**	**32**
48	5,725	115
83	6,058	31
115	6,518	59
128	7,285	21
139	7,946	21
167	9,706	284
178	10,551	480
193	11,216	86

[a]Bold font delineates the dates that bracket the 4.2 kyr event. Table 1 of supplementary material includes raw U and Th measurements and some additional dates that were excluded from the age model because of extraordinarily large errors.

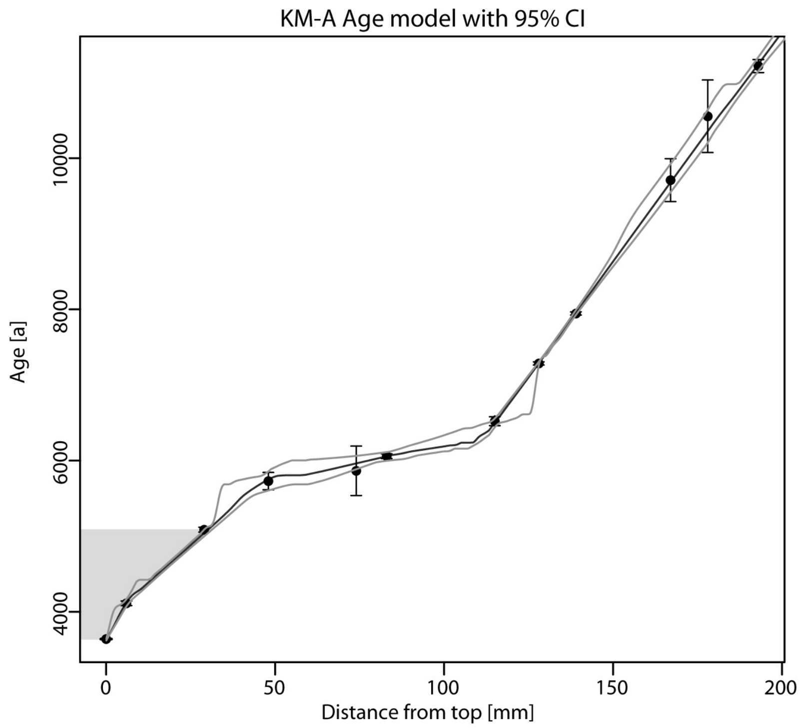

Figure 2. Age model for KM-A stalagmite based on the age-depth relationship of 12 U/Th dates. The age model was generated using StalAGE *Scholz and Hoffmann* [2011] where a Monte Carlo simulation is used to generate linear fits between each progressive subset (3) of dates. The two-sigma analytical uncertainty of each measured date (dots) is represented by the error bars, whereas the 95% uncertainty assessed through the Monte Carlo simulation is represented by the light gray lines. The algorithm produces a realistic representation of age uncertainty through regions of the stalagmite where no radiometric dates are available. The highlighted region in gray represents the time period in which this paper principally is focused. Through this section, the age error is typically less than 30 years. Table 1 of supplementary material contains some additional dates from KM-A through the middle section of the record that were excluded from the age model due to very large age uncertainty. This section of the age model is thus considered only preliminary.

climate proxy, we have no direct empirical evidence or strong theoretical guidance to transfer changes in growth rate into an environmental signal. Thus, with respect to climate variability, all discussion will focus on variations in the $\delta^{18}O$ of the calcite.

2.3. Interpreting the Proxy

Speleothem proxies from the Asian monsoon region have been interpreted to largely reflect changes in monsoon strength because the isotopic composition of the speleothems is highly correlated with changes in local summer insolation due to the precession of the equinoxes [*Wang et al.*, 2001]. Orbital variations affect the $\delta^{18}O$ in speleothems by changing local precipitation processes and/or amounts [*Wang et al.*, 2001; *Cheng et al.*, 2009], such as the ratio of summer-to-spring precipitation (summer rainfall has more negative $\delta^{18}O_p$ than spring precipitation), the intensity of precipitation falling at a given location ("amount effect") [*Dansgaard*, 1964] or changes in the moisture source region [*Pausata et al.*, 2011]. A number of pointed criticisms in the recent literature have required a reconsideration of the appropriate interpretation of the speleothem records from the inland regions of the Asian monsoon suggesting they are not in fact proxies for regional/local precipitation changes, but rather, reflect changes in seasonal precipitation balances and shifts in the isotopic composition of water vapor as a consequence of "upstream" processes over India [*LeGrande and Schmidt*, 2009; *Pausata et al.*, 2011]. Both modeling and observational studies, however, indicate the presence of a consistently robust "amount effect" over the Indian subcontinent and uniformly suggest that isotopic records from this region yield information on monsoon precipitation amounts [*Dayem et al.*, 2010; *Pausata et al.*, 2011; *Vuille et al.*, 2005].

The region of NE India, from where the sample in this study was acquired, is outside of the core Indian monsoon zone [*Berkelhammer et al.*, 2010] where most previous modeling and observational studies of the isotopic composition of ISM precipitation have been done [*Vuille et al.*, 2005; *Sengupta and Sarkar*, 2006]. *Breitenbach et al.* [2010] conducted a 2 year high-resolution sampling campaign in Cherrapunji of $\delta^{18}O_p$, which is likely too brief and sporadic to adequately test the climatic controls on $\delta^{18}O_p$. We thus test the climatic controls on $\delta^{18}O_p$ using an isotope-enabled general circulation model (IsoGSM) [*Yoshimura et al.*, 2008], which provides an extended (multidecadal), albeit synthetic, data set of regional isotopic values and precipitation amount (Figure 3).

IsoGSM reproduces the observed event-scale isotopic variability from *Breitenbach et al.* [2010] with skill ($r^2 = 0.81$, $p << 0.01$) (Figure 3) and the year-to-year variability in precipitation amounts ($r^2 = 0.41$, $p << 0.01$), which gives confidence that the monsoon dynamics in the model are represented sufficiently to generate a time series of $\delta^{18}O_p$ that can be used to test the climatic controls on $\delta^{18}O_p$. As suggested from previous work, we find an inverse relationship between $\delta^{18}O_p$ of monsoon season (May–October) precipitation and monsoon season precipitation amount (Figure 3). A significant relationship is, however, only present when a seasonal-averaging window that includes September and

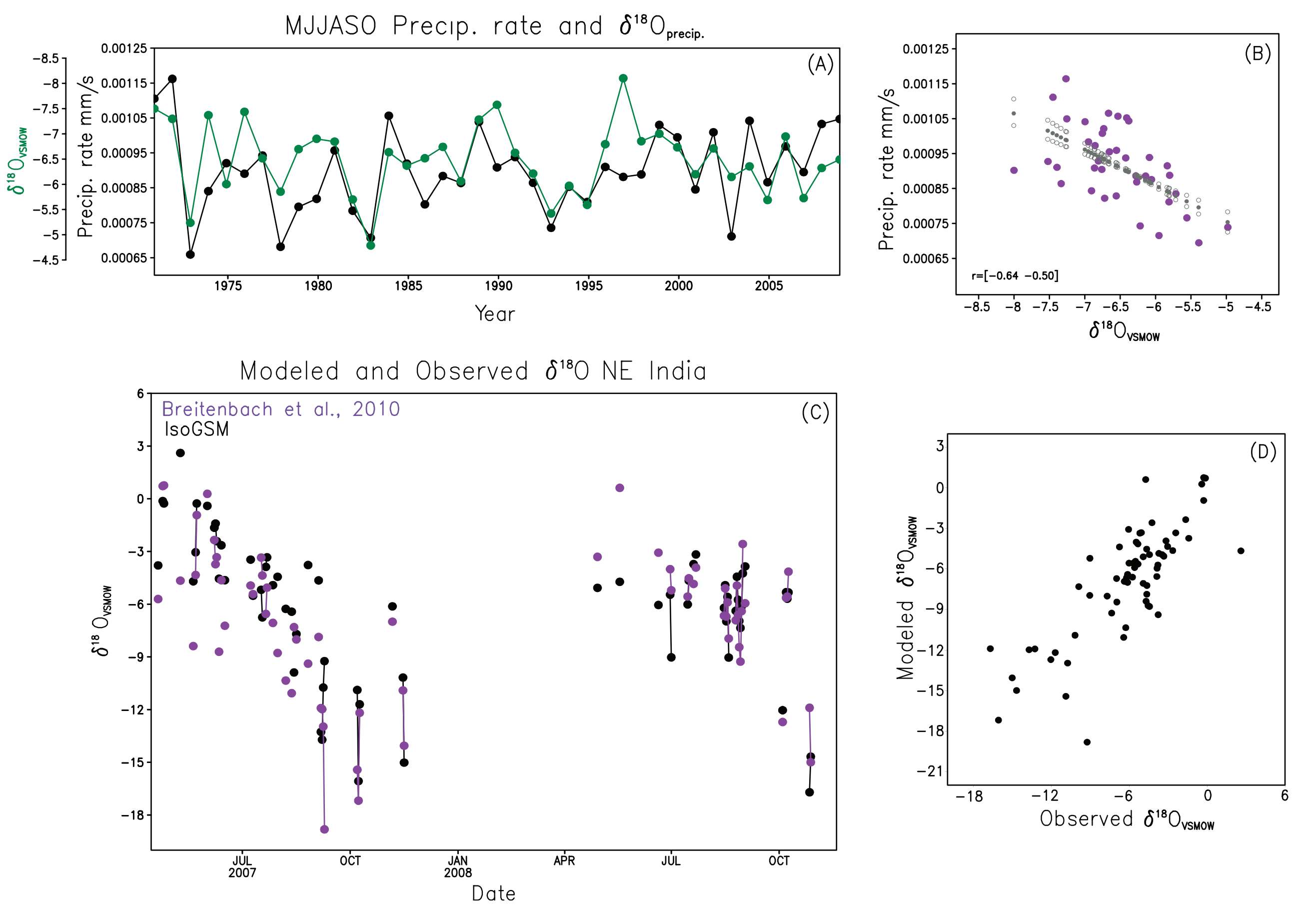

Figure 3. An analysis of the amount effect in NE India: (a) Comparison of modeled precipitation rate and $\delta^{18}O_p$ averaged for MJJASO from 1970 to 2008 from the isotope-enabled general circulation model (IsoGSM) [*Yoshimura et al.*, 2008]. (b) The linear fit between the time series shown in Figure 3a (green) and the gray dots (filled) shows the results of a robust regression analysis, and the open gray dots are the one-sigma uncertainty around this fit. From this, we infer that changes in precipitation rate can account for up to 30% of the observed interannual variability in monsoonal precipitation at this site. (c and d) A comparison between daily observed [*Breitenbach et al.*, 2010] and modeled $\delta^{18}O_p$ in Cherrapunji. This direct daily comparison between model and observation is feasible because of the use of a spectral nudging procedure in the simulation, which forces the model at each time step toward Reanalysis II atmospheric climate fields [*Yoshimura et al.*, 2008]. From here, we infer the model is capable of reproducing the isotopic composition of precipitation at this site and is therefore useful for extrapolation and assessing the climate controls on $\delta^{18}O_p$ as in Figures 3a and 3b.

October is used, suggesting that the presence of an "amount-effect" in this region largely reflects the close relationship between total monsoon precipitation and the timing of monsoon withdrawal [*Fasullo and Webster*, 2003]. Thus, during strong monsoon years, precipitation extends later into autumn [*Fasullo and Webster*, 2003], and the isotopic composition of the accumulated precipitation is relatively depleted as a consequence of these late monsoon season rains, which are the isotopically lightest rains of the year [*Sengupta and Sarkar*, 2006; *Breitenbach et al.*, 2010].

Further empirical evidence of the precipitation signal in the KM-A record is garnered through isotopic analysis of a nearby speleothem record (WS-B from *Sinha et al.* [2011b]), which grew throughout the instrumental era and can thus be calibrated directly against instrumental precipitation records. The record suggests the presence of a negative correlation between $\delta^{18}O$ of the calcite and local precipitation amount and therefore that the inverse relationship between $\delta^{18}O_p$ and precipitation amount as observed in IsoGSM is carried through to the speleothem record.

The relationship between precipitation amount and $\delta^{18}O_p$ however, only accounts for between 20% and 30% of the total isotopic variability. Thus, while some of the variability in the KM-A record may be a direct proxy for monsoon strength, it is critical to acknowledge that changes in $\delta^{18}O$ reflect a myriad of potential climatic processes. *Breitenbach et al.* [2010] and *Sengupta and Sarkar* [2006] discuss how a southerly shift in the locus of convective activity in the Bay of Bengal lead to precipitation that had experienced greater rainout and is therefore more depleted in heavy isotopes. In addition, a change in land surface processes that would shift the proportion of transpiration and bare-soil evaporation would influence $\delta^{18}O_p$ because the former seeds the atmosphere with relatively enriched vapor and the latter with relatively depleted vapor. Last, there is a strong seasonality in $\delta^{18}O_p$ in this region (Figure 3), thus a change in the timing of monsoon onset (which is not particularly sensitive to total monsoon rainfall) [*Fasullo and Webster*, 2003] would produce a change in integrated $\delta^{18}O_p$ value that may not reflect a change in monsoon strength. The multitude of processes influencing $\delta^{18}O_p$ would require a transfer function between $\delta^{18}O_p$ and climate that would be multivariate [*Johnson and Ingram*, 2004], likely nonlinear and, ultimately, nonstationary. Furthermore, changes in the temperature of the chamber and humidity would impart effects on thermodynamic and kinetic fractionation between water and calcite that could produce some small isotopic variability not directly tied to monsoon processes. Until model simulations with isotope tracers and representative 4000 year B.P. boundary conditions are available, we will not attempt to cast the isotopic changes directly into quantitative climate terms.

3. RESULTS

The complete isotopic record (Figure 1) is characterized by a long-term parabolic trend, which is punctuated by a number of multicentennial excursions. The isotopic values in this speleothem are similar to, but more depleted than, modern

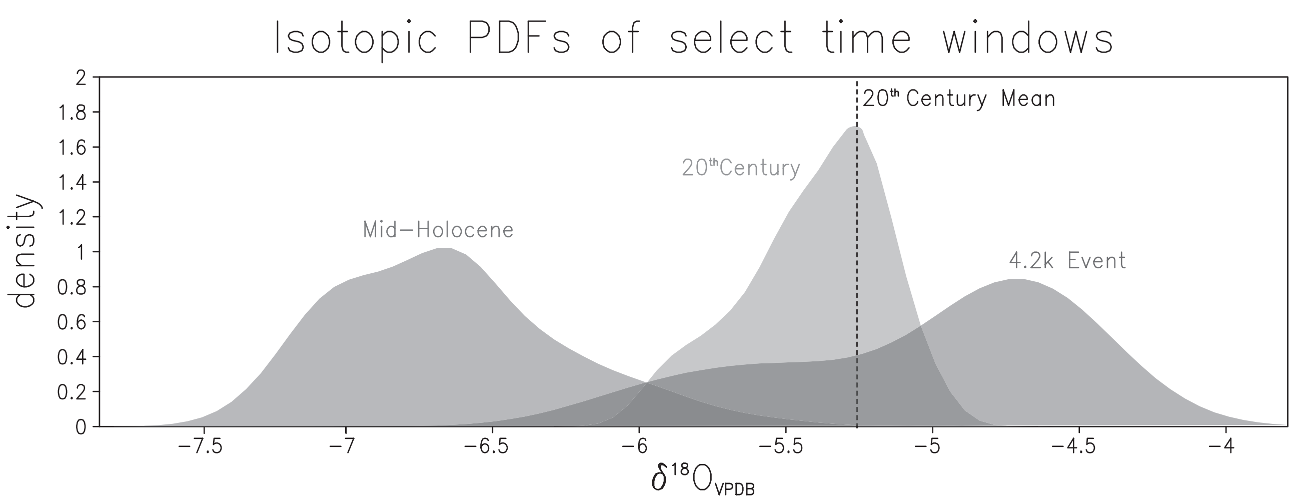

Figure 4. Probability distribution functions of the $\delta^{18}O$ of the KM-A (medium gray) and WS-B (light gray) [*Sinha et al.*, 2011b] stalagmites during selected time windows. The PDFs were created using a nonparametric fit with a normal kernel. The width of the kernel was optimized following the default algorithm in the Matlab Software package. The data for the twentieth century distribution used all the data from the WS-B stalagmite from *Sinha et al.* [2011b], whereas the *4.2 kyr* data used all the data points between 4.1 and 3.8 kyr B.P., and the *mid-Holocene* data is that taken from 7–8 kyr B.P.

calcite values measured from an actively growing sample in a nearby cave (Figure 4) [*Sinha et al.*, 2011b]. The most isotopically enriched values of the entire record occur between 4071 B.P. (±18 years) and 3888 B.P. (±22 years) during which the calcite remained enriched by ~0.8‰ relative to modern values (1.5‰ relative to the background values of the time) for a period of 183 years. The isotopic changes at this time manifested as a two-step process where values experienced a small steplike rise between ~4315 and 4303 years B.P. and experienced a second and more precipitous rise between ~4071 and 4049 years B.P. The abrupt shift occurred over approximately two decades, after which the values stabilized at this relatively enriched state for ~180 years before rapidly returning to previous background values at 3888 years B.P. Comparably enriched isotopic values were periodically reached during the instrumental era for single years but never remained sustained at these enriched levels for more than a year or two [see *Sinha et al.*, 2011b] (see also Figure 4). Thus, the monsoon over NE India at 4000 years B.P. could be considered analogous to end members of the modern monsoon. The only other section of the KM-A record that shows comparably enriched values are those from ~12,000 B.P., which may correspond to the *Younger Dryas*, a period that has been identified from marine and speleothem records as being characterized by having notably diminished monsoon precipitation [*Sinha et al.*, 2005; *Rashid et al.*, 2011].

4. DISCUSSION

4.1. Climate Changes in NE India at 4 kyr B.P.

The monsoon over northeast India appears to have experienced an abrupt excursion at 4000 years B.P., the magnitude of which, in terms of both amplitude and length, exceeds any other event during either the most recent 600 years [*Sinha et al.*, 2011a] or throughout the early to mid-Holocene. Modeling of the isotopic composition of precipitation in this region suggests that a shift toward a consistently earlier monsoon onset or earlier withdrawal could both feasibly explain the observed isotopic enrichment during this time period. The earlier onset enriches isotopic values in the precipitation by including a greater percentage of spring precipitation in the annually weighted accumulation, while the earlier withdrawal reduces the contribution of depleted late-season precipitation, also leading to a more enriched annually weighted precipitate. Early monsoon withdrawal would suggest that the monsoon was weakened at the time [*Fasullo and Webster*, 2003], which is consistent with the findings of *Wang et al.* [2005]. However, as noted earlier in this study and previously by *Breitenbach et al.* [2010], there are a number of additional mechanisms that could have led to an increase in $\delta^{18}O_p$, including a more northerly locus for the convective systems that form in the Bay of Bengal and rainout over northeast India [*Sengupta and Sarkar*, 2006] or a general weakening of monsoon-related convection, which enriches the precipitation by increasing postcondensational evaporation [*Lee and Fung*, 2008].

The strength and/or seasonality of the monsoon is intimately tied to large-scale tropical ocean-atmosphere dynamics with secondary influences associated with land surface processes (i.e., latent heating and albedo) [*Webster*, 1987]. *Abram et al.* [2009] and *Rashid et al.* [2011] have both reviewed SST records from the western Tropical Pacific and IO from this time period and have found that SST patterns in the region likely underwent a formative change with warming in both the Indo-Pacific Warm Pool and eastern IO and cooling on the western margin of the IO. The SST pattern thus may have resembled something akin to a negative Indian Ocean Dipole (IOD) mode, which would have increased divergence over India and reduced the overall strength of monsoon circulation [*Ashok et al.*, 2004]. A similar mechanism involving changes in regional SSTs and their influence on the dynamics of the ITCZ have been called upon to explain a number of other regional climatic changes around 4000 years B.P. including severe droughts in East Africa, Mauritius, and across the Mediterranean [*Gasse*, 2000; *Rijsdijk et al.*, 2011; *Thompson et al.*, 2002; *Cullen et al.*, 2000; *Drysdale et al.*, 2006].

In addition to dynamics within the IO basin, changes in El Niño–Southern Oscillation (ENSO) would have influenced both the seasonality and strength of the monsoon vis-à-vis a zonal shift in the subsiding limb of the Walker cell. *Fasullo and Webster* [2003] find that the timing of monsoon onset is strongly correlated with ENSO such that La Niña conditions lead to an earlier onset. Thus, a change in ENSO would produce a climatic and isotopic influence over this region, and this effect could be modulated (i.e., exacerbated) in the presence of a persistently positive IOD [*Ashok et al.*, 2004]. It may be that positive interactions between conditions in the ENSO domain and regional changes in the IO are needed to produce sustained and significant climate changes in this region. This interpretation is consistent with the findings of *Graham et al.* [2011] who show that in order to effectively model the hydroclimatic changes in Asia during the Medieval Climate Anomaly, the combined influences of both ENSO and the IO must be considered. A short coral record from Vanuatu in the western Tropical Pacific by *Corrège et al.* [2000] hint at the possibility of some extreme ENSO events during this period, but the record is too short to properly assess the conditions at the time. The Ecuadorian lake record of *Moy et al.* [2002], however, indicates nothing anomalous about ENSO conditions during this time period.

Land surface processes could also have been a critical driver in influencing the strength and seasonality of the monsoon through changes in the land-sea thermal gradient or continental recycling of water. The most proximal high-resolution terrestrial record through this time period is the lacustrine cellulose record from the Tibetan Plateau by *Hong et al.* [2003]. This record depicts a significant enrichment in both $\delta^{18}O$ and $\delta^{13}C$ of lake sedimentary cellulose, which reflects either a severe warming and/or drying episode. The multiproxy review of Tibetan Plateau temperatures by *Mischke and Zhang* [2010], based on a suite of lake sediment records and Himalayan ice cores, suggests, contrary to the findings of *Hong et al.* [2003], that there was an abrupt cooling event around 4 kyr B.P. that exceeded in magnitude any other event during the Holocene. These studies together suggest that the Tibetan Plateau experienced an abrupt cool [*Mischke and Zhang*, 2010] and dry [*Hong et al.*, 2003] period in near synchronicity with the isotopic changes in NE India. Cool conditions on the Plateau would be conducive to weakened monsoon circulation, and the dry conditions [i.e., *Hong et al.*, 2003] suggest that the anomalous conditions we report from NE India were regionally pervasive.

4.2. Societal and Dynamical Implications

It is increasingly clear based on a growing number of records spanning across the Mediterranean, Middle East, North Africa, North America, and China [*Weiss*, 2012] that there was a significant large-scale climate excursion at approximately 4 kyr B.P. The new record presented here from Mawmluh Cave in NE India forwards work on this event by providing the first terrestrial record over the Indian subcontinent, which confirms that climate changes at this time were not restricted to regions influenced by the westerlies but also to monsoonal domains. Previous paleoclimate work in the Indus Valley has relied heavily on reconstructions of the flow from the Indus River, which integrates both summer and winter precipitation [*Staubwasser et al.*, 2003]. It is hypothesized that changes in river flow would provide the most tangible link between climate and societal change in this region [*Clift et al.*, 2012; *Staubwasser and Weiss*, 2006]. Recent studies of sediment provenance suggest that significant changes in the drainage pattern of the major Ghaggar-Hakra river system (i.e., the loss of Himalayan snowmelt) significantly predate Indus Valley deurbanization [*Clift et al.*, 2012]. These results imply that when the banks of the river system were densely occupied 4000 years ago, the river was small (perhaps ephemeral) and fed principally by monsoonal precipitation. Because the river had lost much of its Himalayan drainage source, it would have had no buffer against monsoonal precipitation changes. Therefore, the independent reconstruction of monsoonal changes documented here suggests that changes in river flow must still be considered in understanding the deurbanization of the Indus Valley Civilization.

The Mawmluh record also provides a significant improvement with respect to sample resolution and age control, yielding a refined perspective on the duration and onset time of this climate event. As can be seen in Figure 1, a number of records seem to cluster close to one another (e.g., Gulf of Oman, Shabban Deep, and W. North America), but there are also some records, which owing to either hysteresis effects in the proxy (e.g., long karstic residence times), nonlinear proxy response functions (e.g., dust spikes), or lower sampling resolution that tend to blur the exact sequence of change. *Madella and Fuller* [2006] highlight how dating errors in low-resolution proxies can produce marked differences in understanding whether climate events observed in distal sites are causally related and how reconstructed climate events might be related to societal change. For example, the choice of how to apply radiocarbon corrections to the pollen sequences of northwest India will change whether the deurbanization of the Indus Valley Civilization occurred during an anomalously wet or dry period [*Madella and Fuller*, 2006]. In other words, low-resolution records with poor age control can produce antipodal hypotheses regarding climate-cultural linkages. So while understanding the regional cultural responses to climate extends beyond the scope of the study, the Mawmluh cave record cannot be “wiggled” more than a few years in any direction, which reduces any future ambiguities that may be associated with dating errors of monsoonal changes at 4 kyr B.P.

Because of its uniquely large signature, in terms of both magnitude and spatial scope, the climatic changes at this time bring about a number of questions regarding the global climate at this period. *Ding and Wang* [2005] and *Krishnan et al.* [2009] have shown that changes in the ISM can influence much of the Northern Hemisphere by producing a Rossby wave dispersion pattern that affects the location and strength of the midlatitude westerlies. The change in midlatitude westerlies, in turn, enhances the intrusion of dry extratropical air into the monsoon system, which further suppresses the monsoon. In this way, a positive feedback loop between the monsoon and westerlies occurs (i.e., weaker monsoon $\Rightarrow$ change in westerlies $\Rightarrow$ even weaker monsoon) that can generate circumglobal pressure anomalies and provide a theoretical link between proxies that would be sensitive to monsoonal changes such as in NE India and those records that would be influenced also by westerly flow such as drainage from the Indus River or the ice core and peat records from the western United States. The trigger to initiate this feedback loop could either arise from a perturbation of the westerlies from a high-latitude forcing (i.e., the North Atlantic) [*Bond et al.*, 1997; *Hong et al.*, 2003] or from dynamics within the tropics. The latter was discussed previously by *Booth et al.* [2005], who suggested that a strong SST gradient in the eastern Tropical Pacific coupled with anomalous warmth in the IO could produce global climate anomalies akin to those experienced between 1998 and 2002 (i.e., *The Perfect Ocean for Drought*) [*Hoerling and Kumar*, 2003]. However, the challenge in applying the dynamics described explicitly by either *Krishnan et al.* [2009] or *Hoerling and Kumar* [2003] toward an understanding of the changes at 4000 years B.P. is that while these feedback operate effectively on short timescales, it has never been tested as to whether they could produce an anomalous climate mode for decades to centuries.

Despite what appears to be growing evidence for a widespread climate event at this time, it also must be acknowledged that a number of locations, which theoretically should show a signature of this event, appear complacent. For example, the Qunf cave record from Oman [*Fleitmann et al.*, 2003] and the Dongge record from China [*Wang et al.*, 2005], which are both touted as proxies of the ISM, lack a signature that is congruous with the magnitude of change observed in NE India. It may be that because neither record is situated directly in the monsoon domain, they lack the sensitivity to the ISM of the NE India record. Further, with respect to an arid region such as Oman, the presence of an overlooked hiatus or period of very slow growth may plausibly explain the absence of a 4 kyr B.P. excursion. It is also clear both in the paleo [*Sinha et al.*, 2011b] and modern [*Conroy and Overpeck*, 2011] contexts that ISM precipitation is characterized by complex spatial heterogeneity. For example, NE India can exhibit antiphased behavior with central India. In this respect, reliance on a single record from NE India to characterize the ISM is tenuous, and therefore, it is acknowledged that additional records from the Indian continent are urgently needed to provide a conclusive picture of monsoonal changes at 4000 years B.P.

5. CONCLUSIONS

There are some tempting hints that the climate system at 4000 years B.P. may serve as a remarkable instance of a large-scale, abrupt Holocene climate event. The event is particularly interesting because the climate at the time was, in many ways, comparable to today's [*Corrège et al.*, 2000]. However, there still exist a number of major impediments with respect to quantitatively understanding this climate event. Much of the uncertainty stems from the fact that most of the available proxy data, including the record presented here, are only qualitative. General circulation model simulations that begin with realistic 4 kyr B.P. boundary conditions and are perturbed with a variety of forcings would be a useful starting point to produce hypotheses for the dynamical underpinnings of this event. Similar efforts have been successfully undertaken to understand potential mechanisms that lead to the 8.2 kyr event [*LeGrande et al.*, 2006]. Ultimately, the model simulations would need to be either systematically linked offline to individual proxy process models or simulations that include tracers would be needed to place the diverse proxies into common quantitative climate terms. This technique has been effective in understanding the complex signal across the Last Glacial Maximum monsoon speleothem proxies [*Pausata et al.*, 2011] and could help in this context to shed light on why the signature of the 4 kyr B.P. signal in Omani [*Fleitmann et al.*, 2003], Chinese [*Wang et al.*, 2005], Middle Eastern [*Bar-Matthews et al.*, 1999], and Indian (this study) speleothem records have such distinct differences. This effort is needed before the proxy records can be successfully operationalized by archaeologists in such a way as to make a substantive comment on the role that hydrological changes played in the cultural changes across the Middle East, India, and North Africa at this time [*Weiss et al.*, 1993].

APPENDIX A: SUPPLEMENTARY MATERIAL

Supplementary data (M. Berkelhammer et al., Mawmluh Cave, India Holocene Oxygen Isotope Data, http://www.ncdc.noaa.gov/paleo/speleothem.html, IGBP PAGES/World Data Center for Paleoclimatology, Data Contribution Series 2010-011, NOAA/National Climatic Data Center Paleoclimatology Program, Boulder, Colorado, 2012) have been permanently archived and are freely accessible. Table 1 contains $\delta^{18}O$ data from a calcitic stalagmite (KM-A) from Mawmluh Cave, located in Cherrapunji, Meghalaya in northeast India. Dating is based on eight U/Th series dates.

Acknowledgments. The authors would like to thank Miguel Rincon for the assistance with the isotopic measurements and Brian Khapran-Daly, Robert Berkelhammer, and Kevin Cannariato for assistance with the field work. This work was supported, in part, by the National Science Foundation grants to A.S. (ATM: 0823554 and AGS: 1103360) and the National Science Foundation of China grant to HC (41140016).

REFERENCES

Abram, N., H. McGregor, M. Gagan, W. Hantoro, and B. Suwargadi (2009), Oscillations in the southern extent of the Indo-Pacific Warm Pool during the mid-Holocene, *Quat. Sci. Rev.*, *28*(25–26), 2794–2803.

Arz, H., F. Lamy, and J. Patzold (2006), A pronounced dry event recorded around 4.2 ka in brine sediments from the northern Red Sea, *Quat. Res.*, *66*(3), 432–441.

Ashok, K., Z. Y. Guan, N. H. Saji, and T. Yamagata (2004), Individual and combined influences of ENSO and the Indian Ocean Dipole on the Indian summer monsoon, *J. Clim.*, *17*(16), 3141–3155.

Bar-Matthews, M., A. Ayalon, A. Kaufman, and G. Wasserburg (1999), The Eastern Mediterranean paleoclimate as a reflection of regional events: Soreq cave, Israel, *Earth Planet. Sci. Lett.*, *166* (1–2), 85–95.

Berkelhammer, M., A. Sinha, M. Mudelsee, H. Cheng, R. Edwards, and K. Cannariato (2010), Persistent multidecadal power of the Indian Summer Monsoon, *Earth Planet. Sci. Lett.*, *290*(1–2), 166–172.

Bond, G., W. Showers, M. Cheseby, R. Lotti, P. Almasi, P. Demenocal, P. Priore, H. Cullen, I. Hajdas, and G. Bonani (1997), A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates, *Science*, *278*(5341), 1257–1266.

Booth, R., S. Jackson, S. Forman, J. Kutzbach, E. Bettis, J. Kreigs, and D. Wright (2005), A severe centennial-scale drought in midcontinental North America 4200 years ago and apparent global linkages, *The Holocene*, *15*(3), 321–328.

Borgaonkar, H., A. Sikder, S. Ram, and G. Pant (2010), El Niño and related monsoon drought signals in 523-year-long ring width records of teak (Tectona grandis LF) trees from south India, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *285*(1–2), 74–84.

Breitenbach, S. (2009), Changes in monsoonal precipitation and atmospheric circulation during the Holocene reconstructed from stalagmites from northeastern India, Ph.D. thesis, Dtsch. GeoForschungsZentrum GFZ, Potsdam, Germany.

Breitenbach, S., J. Adkins, H. Meyer, N. Marwan, K. Kumar, and G. Haug (2010), Strong influence of water vapor source dynamics on stable isotopes in precipitation observed in Southern Meghalaya, NE India, *Earth Planet. Sci. Lett.*, *292*(1–2), 212–220.

Buckley, B., K. Palakit, K. Duangsathaporn, P. Sanguantham, and P. Prasomsin (2007), Decadal scale droughts over northwestern Thailand over the past 448 years: Links to the tropical Pacific and Indian Ocean sectors, *Clim. Dyn.*, *29*(1), 63–71.

Buckley, B., K. Anchukaitis, D. Penny, R. Fletcher, E. Cook, M. Sano, L. Nam, A. Wichienkeeo, T. Minh, and T. Hong (2010), Climate as a contributing factor in the demise of Angkor, Cambodia, *Proc. Natl. Acad. Sci. U. S. A.*, *107*(15), 6748–6752.

Cheng, H., R. Edwards, W. Broecker, G. Denton, X. Kong, Y. Wang, R. Zhang, and X. Wang (2009), Ice age terminations, *Science*, *326*(5950), 248–252.

Clift, P., et al. (2012), U-Pb zircon dating evidence for a Pleistocene Sarasvati River and capture of the Yamuna River, *Geology*, *40*(3), 211–214.

Conroy, J., and J. Overpeck (2011), Regionalization of present-day precipitation in the Greater Monsoon Region of Asia, *J. Clim.*, *24* (15), 4073–4095, doi:10.1175/2011JCLI4033.1.

Cook, E., K. Anchukaitis, B. Buckley, R. DArrigo, G. Jacoby, and W. Wright (2010), Asian monsoon failure and megadrought during the last millennium, *Science*, *328*(5977), 486–489.

Corrège, T., T. Delcroix, J. Récy, W. Beck, G. Cabioch, and F. Le Cornec (2000), Evidence for stronger El Niño-Southern Oscillation (ENSO) events in a mid-Holocene massive coral, *Paleoceanography*, *15*(4), 465–470.

Cullen, H., P. DeMenocal, S. Hemming, G. Hemming, F. Brown, T. Guilderson, and F. Sirocko (2000), Climate change and the collapse of the Akkadian empire: Evidence from the deep sea, *Geology*, *28*(4), 379–382.

Dansgaard, W. (1964), Stable isotopes in precipitation, *Tellus*, *16*, 436–468.

Dayem, K., P. Molnar, D. Battisti, and G. Roe (2010), Lessons learned from oxygen isotopes in modern precipitation applied to interpretation of speleothem records of paleoclimate from eastern Asia, *Earth Planet. Sci. Lett.*, *295*(1–2), 219–230.

Ding, Q., and B. Wang (2005), Circumglobal teleconnection in the Northern Hemisphere summer, *J. Clim.*, *18*(17), 3483–3505.

Drysdale, R., G. Zanchetta, J. Hellstrom, R. Maas, A. Fallick, M. Pickett, I. Cartwright, and L. Piccini (2006), Late Holocene drought responsible for the collapse of Old World civilizations is recorded in an Italian cave flowstone, *Geology*, *34*(2), 101–104.

Enzel, Y., L. Ely, S. Mishra, R. Ramesh, R. Amit, B. Lazar, S. Rajaguru, V. Baker, and A. Sandler (1999), A high-resolution Holocene environmental changes in the Thar Desert, northwestern India, *Science*, *284*, 125–128.

Fasullo, J., and P. Webster (2003), A hydrological definition of Indian monsoon onset and withdrawal, *J. Clim.*, *16*(19), 3200–3211.

Fleitmann, D., S. J. Burns, M. Mudelsee, U. Neff, J. Kramers, A. Mangini, and A. Matter (2003), Holocene forcing of the Indian monsoon recorded in a stalagmite from Southern Oman, *Science*, *300*(5626), 1737–1739.

Gasse, F. (2000), Hydrological changes in the African tropics since the Last Glacial Maximum, *Quat. Sci. Rev.*, *19*(1–5), 189–211.

Graham, N., C. Ammann, D. Fleitmann, K. Cobb, and J. Luterbacher (2011), Support for global climate reorganization during the "Medieval Climate Anomaly", *Clim. Dyn.*, *37*(5–6), 1217–1245.

Hoerling, M., and A. Kumar (2003), The perfect ocean for drought, *Science*, *299*(5607), 691–694.

Hong, Y., et al. (2003), Correlation between Indian Ocean summer monsoon and North Atlantic climate during the Holocene, *Earth Planet. Sci. Lett.*, *211*(3–4), 371–380.

Hoyos, C. D., and P. J. Webster (2007), The role of intraseasonal variability in the nature of Asian monsoon precipitation, *J. Clim.*, *20*(17), 4402–4424.

Johnson, K. R., and B. L. Ingram (2004), Spatial and temporal variability in the stable isotope systematics of modern precipitation in China: Implications for paleoclimate reconstructions, *Earth Planet. Sci. Lett.*, *220*(3–4), 365–377.

Krishnan, R., V. Kumar, M. Sugi, and J. Yoshimura (2009), Internal feedbacks from monsoon-midlatitude interactions during droughts in the Indian summer monsoon, *J. Atmos. Sci.*, *66*(3), 553–578.

Lee, J. E., and I. Fung (2008), "Amount effect" of water isotopes and quantitative analysis of post-condensation processes, *Hydrol. Processes*, *22*(1), 1–8.

LeGrande, A. N., and G. A. Schmidt (2009), Sources of Holocene variability of oxygen isotopes in paleoclimate archives, *Clim. Past*, *5*, 1133–1162.

LeGrande, A. N., G. A. Schmidt, D. T. Shindell, C. V. Field, R. L. Miller, D. M. Koch, G. Faluvegi, and G. Hoffmann (2006), Consistent simulations of multiple proxy responses to an abrupt climate change event, *Proc. Natl. Acad. Sci. U. S. A.*, *103*(4), 837–842.

Levermann, A., J. Schewe, V. Petoukhov, and H. Held (2009), Basic mechanism for abrupt monsoon transitions, *Proc. Natl. Acad. Sci. U. S. A.*, *106*(49), 20,572–20,577.

Loschnigg, J., and P. Webster (2000), A coupled ocean-atmosphere system of SST modulation for the Indian Ocean, *J. Clim.*, *13*(19), 3342–3360.

Madella, M., and D. Fuller (2006), Palaeoecology and the Harappan civilisation of South Asia: A reconsideration, *Quat. Sci. Rev.*, *25* (11–12), 1283–1301.

Meehl, G. (1993), A coupled air-sea biennial mechanism in the tropical Indian and Pacific regions: Role of the ocean, *J. Clim.*, *6*, 31–41.

Meehl, G., and J. Arblaster (2002), The tropospheric biennial oscillation and Asian-Australian monsoon rainfall, *J. Clim.*, *15*(7), 722–744.

Mischke, S., and C. Zhang (2010), Holocene cold events on the Tibetan Plateau, *Global Planet. Change*, *72*(3), 155–163.

Misra, V. (1984), Climate, a factor in the rise and fall of the Indus Civilization: Evidence from Rajasthan and beyond, in *Frontiers of the Indus Civilization*, edited by B. B. Lal and S. P. Gupta, pp. 461–490, Books & Books, New Delhi, India.

Moy, C., G. Seltzer, D. Robdell, and D. Anderson (2002), Variability of El Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch, *Nature*, *420*, 162–165, doi:10.1038/nature01194.

Murata, F., T. Hayashi, J. Matsumoto, and H. Asada (2007), Rainfall on the Meghalaya plateau in northeastern India: One of the rainiest places in the world, *Nat. Hazards*, *42*(2), 391–399.

Pausata, F., D. Battisti, K. Nisancioglu, and C. Bitz (2011), Chinese stalagmite $\delta^{18}O$ controlled by changes in the Indian monsoon during a simulated Heinrich event, *Nat. Geosci.*, *4*(7), 474–480.

Rashid, H., E. England, L. Thompson, and L. Polyak (2011), Late glacial to Holocene Indian summer monsoon variability based upon sediment, *Terr. Atmos. Ocean. Sci.*, *22*(2), 215–228.

Rijsdijk, K., et al. (2011), Mid-Holocene (4200 kyr BP) mass mortalities in Mauritius (Mascarenes): Insular vertebrates resilient to climatic extremes but vulnerable to human impact, *The Holocene*, *21*(8), 1179–1194.

Sano, M., B. Buckley, and T. Sweda (2009), Tree-ring based hydroclimate reconstruction over northern Vietnam from Fokienia hodginsii: Eighteenth century mega-drought and tropical Pacific influence, *Clim. Dyn.*, *33*(2), 331–340.

Schewe, J., A. Levermann, and H. Cheng (2011), A critical humidity threshold for monsoon transitions, *Clim. Past Discuss.*, *7*, 1737–1765.

Scholz, D., and D. Hoffmann (2011), StalAge-An algorithm designed for construction of speleothem age models, *Quat. Geochronol.*, *6*(3–4), 369–382.

Sengupta, S., and A. Sarkar (2006), Stable isotope evidence of dual (Arabian Sea and Bay of Bengal) vapour sources in monsoonal precipitation over north India, *Earth Planet. Sci. Lett.*, *250*(3–4), 511–521.

Singh, G., R. Wasson, and D. Agrawal (1990), Vegetational and seasonal climatic changes since the last full glacial in the Thar Desert, northwestern India, *Rev. Palaeobot. Palynol.*, *64*(1–4), 351–358.

Sinha, A., K. G. Cannariato, L. D. Stott, H. C. Li, C. F. You, H. Cheng, R. L. Edwards, and I. B. Singh (2005), Variability of Southwest Indian summer monsoon precipitation during the Boiling-Allerod, *Geology*, *33*(10), 813–816.

Sinha, A., K. G. Cannariato, L. D. Stott, H. Cheng, R. L. Edwards, M. G. Yadava, R. Ramesh, and I. B. Singh (2007), A 900-year (600 to 1500 A.D.) record of the Indian summer monsoon precipitation from the core monsoon zone of India, *Geophys. Res. Lett.*, *34*, L16707, doi:10.1029/2007GL030431.

Sinha, A., M. Berkelhammer, L. Stott, M. Mudelsee, H. Cheng, and J. Biswas (2011a), The leading mode of Indian Summer Monsoon precipitation variability during the last millennium, *Geophys. Res. Lett.*, *38*, L15703, doi:10.1029/2011GL047713.

Sinha, A., L. Stott, M. Berkelhammer, H. Cheng, R. Edwards, B. Buckley, M. Aldenderfer, and M. Mudelsee (2011b), A global context for megadroughts in monsoon Asia during the past millennium, *Quat. Sci. Rev.*, *30*, 47–62.

Staubwasser, M., and H. Weiss (2006), Holocene climate and cultural evolution in late prehistoric–early historic West Asia, *Quat. Res.*, *66*(3), 372–387.

Staubwasser, M., F. Sirocko, P. M. Grootes, and M. Segl (2003), Climate change at the 4.2 ka BP termination of the Indus valley civilization and Holocene south Asian monsoon variability, *Geophys. Res. Lett.*, *30*(8), 1425, doi:10.1029/2002GL016822.

Thompson, L., et al. (2002), Kilimanjaro ice core records: Evidence of Holocene climate change in tropical Africa, *Science*, *298* (5593), 589–593.

Vuille, M., M. Werner, R. S. Bradley, and F. Keimig (2005), Stable isotopes in precipitation in the Asian monsoon region, *J. Geophys. Res.*, *110*, D23108, doi:10.1029/2005JD006022.

Wagner, B., A. Lotter, N. Nowaczyk, J. Reed, A. Schwalb, R. Sulpizio, V. Valsecchi, M. Wessels, and G. Zanchetta (2009), A 40,000-year record of environmental change from ancient Lake Ohrid (Albania and Macedonia), *J. Paleolimnol.*, *41*(3), 407–430.

Wang, Y. J., H. Cheng, R. L. Edwards, Z. S. An, J. Y. Wu, C. C. Shen, and J. A. Dorale (2001), A high-resolution absolute-dated Late Pleistocene monsoon record from Hulu Cave, China, *Science*, *294*(5550), 2345–2348.

Wang, Y. J., H. Cheng, R. L. Edwards, Y. Q. He, X. G. Kong, Z. S. An, J. Y. Wu, M. J. Kelly, C. A. Dykoski, and X. D. Li (2005), The Holocene Asian monsoon: Links to solar changes and North Atlantic climate, *Science*, *308*(5723), 854–857.

Webster, P. (1987), The elementary monsoon, in *Monsoon*, edited by J. Fein and P. Stephens, pp. 3–32, John Wiley, New York.

Weiss, H. (2012), Altered trajectories: The intermediate Bronze Age, in *The Oxford Handbook of the Archaeology of the Levant*, edited by A. Killebrew and M. Steiner, Oxford Univ. Press, Oxford, U. K., in press.

Weiss, H., M. Courty, W. Wetterstrom, F. Guichard, L. Senior, R. Meadow, and A. Curnow (1993), The genesis and collapse of third millennium north Mesopotamian civilization, *Science*, *261* (5124), 995–1004.

Yoshimura, K., M. Kanamitsu, D. Noone, and T. Oki (2008), Historical isotope simulation using Reanalysis atmospheric data, *J. Geophys. Res.*, *113*, D19108, doi:10.1029/2008JD010074.

Zhang, P. Z., et al. (2008), A test of climate, sun, and culture relationships from an 1810-year Chinese cave record, *Science*, *322*(5903), 940–942.

M. Berkelhammer, Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309, USA. (max.berkelhammer@colorado.edu)

H. Cheng, Institute of Global Environmental Change, Xian Jiaotong University, Shanghai, China.

F. S. R. Pausata, Bjerknes Center for Climate Research, Bergen, Norway.

A. Sinha, Department of Earth Sciences, California State University, Dominguez Hills, Carson, CA, USA.

L. Stott, Department of Earth Sciences, University of Southern California, Los Angeles, CA, USA.

K. Yoshimura, Atmosphere and Ocean Research Institute, University of Tokyo, Tokyo, Japan.