Quaternary Science Reviews 30 (2011) 47–62

no. 1-2

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

A global context for megadroughts in monsoon Asia during the past millennium

Ashish Sinha [a,*], Lowell Stott [b], Max Berkelhammer [b], Hai Cheng [c,d], R. Lawrence Edwards [d], Brendan Buckley [e], Mark Aldenderfer [f], Manfred Mudelsee [g,h]

[a] Department of Earth Science, California State University Dominguez Hills, Carson, CA 90747, USA
[b] Department of Earth Science, University of Southern California, Los Angeles, CA 90747, USA
[c] Institute of Global Environmental Change, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China
[d] Department of Geology and Geophysics, University of Minnesota, MN 55455, USA
[e] Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA
[f] School of Social Sciences, Humanities and Arts, University of California Merced, CA 95343, USA
[g] Climate Risk Analysis, Hanover, Germany
[h] Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany

ARTICLE INFO

Article history:
Received 21 March 2010
Received in revised form
18 August 2010
Accepted 11 October 2010

ABSTRACT

Proxy reconstructions of precipitation from central India, north-central China, and southern Vietnam reveal a series of monsoon droughts during the mid 14th–15th centuries that each lasted for several years to decades. These monsoon *megadroughts* have no analog during the instrumental period. They occurred in the context of widespread thermal and hydrologic climate anomalies marking the onset of the Little Ice Age (LIA) and appear to have played a major role in shaping significant regional societal changes at that time. New tree ring-width based reconstructions of monsoon variability suggest episodic and widespread reoccurrences of monsoon megadroughts continued throughout the LIA. Although the El-Niño Southern Oscillation (ENSO) plays an important role in monsoon variability, there is no conclusive evidence to suggest that these megadroughts were associated with anomalous sea surface temperature anomalies that were solely the result of ENSO-like variability in the tropical Pacific. Instead, the causative mechanisms of these megadroughts may reside in protracted changes in the synoptic-scale monsoon climatology of the Indian Ocean. Today, the intra-seasonal monsoon variability is dominated by 'active' and the 'break' spells – two distinct oscillatory modes of monsoon that have radically different synoptic scale circulation and precipitation patterns. We suggest that protracted *locking* of the monsoon into the "break-dominated" mode – a mode that favors reduced precipitation over the Indian sub-continent and SE Asia and enhanced precipitation over the equatorial Indian Ocean, may have caused these exceptional droughts. Impetus for periodic locking of the monsoon into this mode may have been provided by cooler temperatures at the extratropical latitudes in the Northern Hemisphere which forced the mean position of the Inter-Tropical Convergence Zone (ITCZ) further southward in the Indian Ocean.

1. Introduction

Although modern industrial societies can be resilient to short-term droughts, the potential consequences that would be associated with a drought lasting years to decades, or even a century (*megadrought*[1]), constitutes one of the greatest threats to human welfare. This is a particular serious threat for the predominantly agrarian-based societies of monsoon Asia, where the lives of billions of people are tightly intertwined with the annual monsoon cycle. Even modest departures from normal monsoon onset or the spatial distribution of rainfall amount in these regions can bring widespread social and economic hardship. The nexus between droughts, famines, and mass mortality that has plagued India for centuries[2] has only recently been overcome (Dre'ze, 1995). Nonetheless, much of India's farm sector, which accounts for one-sixth of

* Corresponding author. Tel.: +1 951 243 7111.
E-mail address: asinha@usc.edu (A. Sinha).

[1] A formally accepted climatological definition of megadrought does not exist. Meehl and Hu (2006) define megadrought as based on a "duration threshold as an 11-yr running mean of regional area-averaged precipitation anomalies less than zero for at least 20 consecutive years".

[2] Not all droughts in India before the 1960s caused famines and nor all famines resulted from droughts.

0277-3791/$ – see front matter
doi:10.1016/j.quascirev.2010.10.005

the gross domestic product (GDP), remains highly vulnerable to major shifts in monsoon precipitation patterns (Webster et al., 1998; Gadgil and Gadgil, 2006). This vulnerability was highlighted in 2002, when much of the Indian sub-continent suffered one of the most severe droughts in its recorded history, resulting in a major drop in food production and the GDP (Gadgil et al., 2004). The severity and large spatial extent of this unanticipated drought serves as a grim reminder that unless contingency plans are in place well in advance, even a single season of anomalous monsoon rainfall in densely populated regions can have disastrous consequences. This looming threat is likely to become even more acute in coming decades as groundwater supplies in India, which provide a buffer against precipitation departures, become increasingly depleted (Rodell et al., 2009).

The monsoon precipitation variability and drought recurrence history during the past 150 years in the Indian sub-continent can be gauged from the instrument record of area-weighted monsoon rainfall (starting ca, 1871 AD), the so called 'All India Monsoon Rainfall' (AIR) series (Parthasarathy et al., 1995) (Fig. 1). Observational data indicate that over large parts of India, a reduction in the AIR of only 10% (~1 standard deviation) is often the difference between a *good* monsoon season and a drought (Shukla, 1987; Sikka, 1999, 2003) (Fig. 1). In years when the monsoon rainfall is 20% below the mean, nearly the entire Indian sub-continent and the adjacent regions are in the grip of a severe drought, and the monsoon in these years is considered a *failure* (Shukla, 1987). For example, the drought in AD 1918 was the most spatially extensive event, affecting about 70% of India. Similarly severe droughts occurred in 1899 (70%), 1877 (60%), 1972 (53%), 1987 (48%) and 2002 (20%). Fortunately, such monsoon *failures* have occurred only sporadically and none have lasted for more than 2 consecutive monsoon seasons (Fig. 1). In fact, during the last 150 years, there have never been more than 5 monsoon droughts in any continuous 10 year interval in India (Fig. 1). Thus, on the basis of the instrumental record, protracted monsoon failures lasting many years to decades do not appear to be an intrinsic aspect of present-day Indian monsoon variability. While reassuring, it is important to bear in mind that this assessment has been made from a relatively short instrumental record and is therefore unlikely to have captured the full range of monsoon precipitation and drought variability as we have illustrated in this paper.

Previously, we have used the oxygen isotopic composition ($\delta^{18}O$) record of a speleothem from Dandak Cave (19 °N, 82 °E) located in central-eastern India to document Indian monsoon rainfall variations between AD 600–1500 (Fig. 2) (Sinha et al., 2007; Berkelhammer et al., 2010). The location of this record is significant for several reasons (Fig. 3). Local monsoon rainfall variability at this site is strongly correlated with the variations in monsoon rainfall over the core monsoon zone (CMZ) – a broad NW-SE trending region encompassing the central region of the Indian sub-continent ($r = 0.39$ $p < 0.0002$) (Gadgil, 2003; Rajeevan et al., 2010) (Figs. S1 and S2).The inter-annual variability of monsoon rainfall in the CMZ is strongly correlated with AIR ($r = 0.91$ $p < 0.0001$; Rajeevan et al., 2010) (Fig. S3) and is negatively correlated with various ENSO indices (Ashok et al., 2004). In addition, the monsoon rainfall in the CMZ is strongly influenced by 'active' and 'break' spells of the monsoon, which are days (3–5) to weeks (2–4) long episodes of enhanced and deficient rainfall, respectively (e.g., Sikka, 1980) (Fig. S4). These oscillatory modes of monsoon are manifestations of sub-seasonal fluctuations in the mean position of the continental tropical convergence zone (CTCZ) over the CMZ (e.g., Sikka and Gadgil, 1980; Lawrence and Webster, 2001; Goswami et al., 2006a). Extended periods of break monsoon (lasting >14 days), particularly during the months of July and August, have been associated with nearly every major drought in the Indian sub-continent during the instrumental interval (Joseph et al., 2009). The occurrence of one of the longest recorded breaks during the 2002 drought serves as a clear embodiment of this phenomenon (Fig. 3) (Krishnan et al., 2006; Gadgil et al., 2007; Rajeevan et al., 2010). The spatial pattern of Outgoing Longwave Radiation (OLR) and precipitation anomalies over the Indian sub-continent, SE Asia, and the Indian Ocean (IO) observed during these extended break periods are distinct from anomalies during the warm phases of ENSO, suggesting the importance of non-ENSO dynamics, particularly the role of convection over the Equatorial Indian Ocean, in causing monsoon droughts in this region (Gadgil et al., 2004, 2007; Rajeevan et al., 2010).

In light of the aforementioned observations, we consider the reconstructed history of monsoon and drought variability in Dandak Cave record to be broadly representative of overall variations in the strength of the Indian monsoon. The Dandak Cave record, when considered together with other regional proxy monsoon records, may thus shed light on the relative importance of drought-inducing mechanisms associated with ENSO and non-ENSO climate dynamics. Utilizing the observed and modeled relationship between the $\delta^{18}O$ in precipitation and the amount of monsoon rainfall for the CMZ, we objectively delineate a number of monsoon droughts as well as pluvial events in our record. The interval between AD 950 and 1250 emerges as an interval of generally stronger monsoon rainfall. On the other hand, droughts occurred frequently on either side of this interval with nearly every major drought in our record, independently corroborated by historical accounts of famine in India (Sinha et al., 2007). In particular, between AD 1250 and 1450 the Dandak Cave record contains

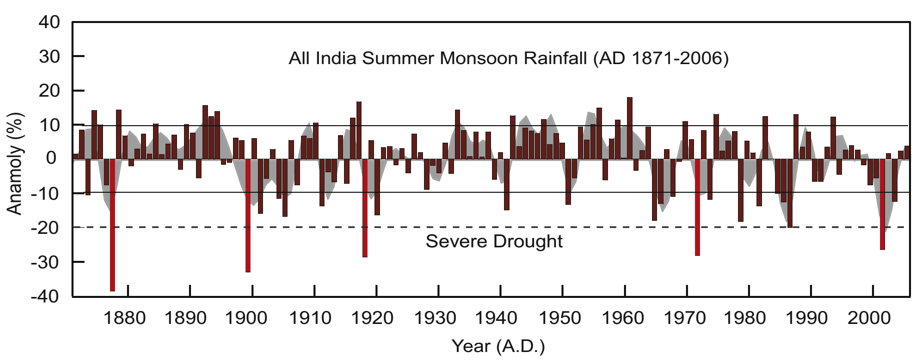

Fig. 1. Inter-annual variations of the All India summer monsoon (JJAS) rainfall (AIR) anomaly expressed as percent departure from its long-term mean (~850 mm). Data was obtained from the Indian Institute of Tropical Meteorology (www.tropmet.res.in). The decadal-scale monsoon rainfall variability is highlighted by a low pass Gaussian (>8 year) filter (gray shading). Spatially widespread severe droughts in India (AIR >20% below mean) are indicated by red bars (for interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

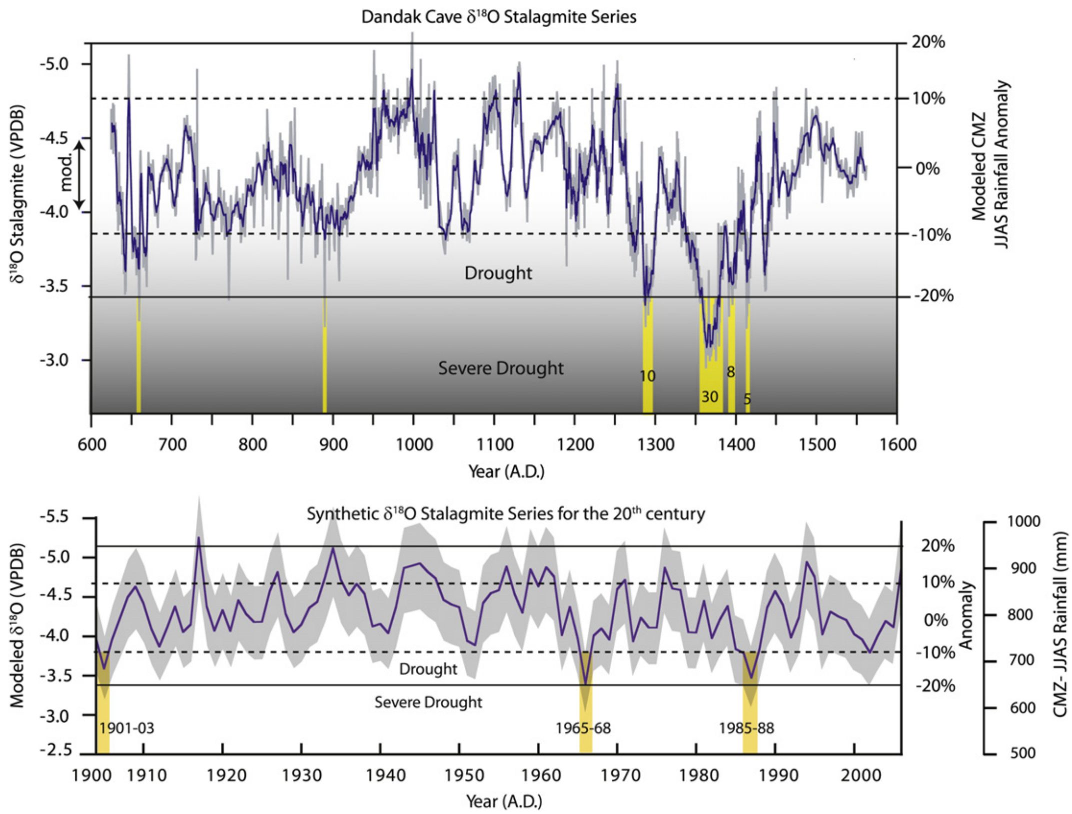

Fig. 2. Dandak Cave stalagmite $\delta^{18}O$ record (top panel). Raw data is shown in gray overlain by a 3 point running mean curve (blue). The range of modern $\delta^{18}O$ values of calcite in Dandak Cave (~AD 1950–2006 AD) is shown by a double arrow. Dandak $\delta^{18}O$ values are converted into JJAS precipitation anomalies (dashed and solid horizontal lines) expressed as percentage departure from the 20th century mean (see text for further explanation). The $\delta^{18}O$ values higher than −3.8‰ and −3.2‰ delineate intervals of inferred drought and megadroughts (yellow bars) implying more than 10% and 20% decrease in monsoon rainfall, respectively. The bottom panel shows a synthetic 2-year smoothed stalagmite $\delta^{18}O$ time series for the 20th century constructed by estimating the slope of the amount effect in the core monsoon zone (CMZ) by regressing modeled output of isotopic composition of JJAS precipitation from the isotope-enabled AGCM simulation IsoGSM against the JJAS instrumental rainfall amount from the CMZ (see Fig. S5). Yellow bars indicate three episodes of weaker monsoon (when the monsoon rainfall in 2 out of 3 successive years was below 10% of mean) during the instrumental period(for interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

prominent decade to multi-decade long intervals of severe droughts. As our analysis in Section 2 will highlight, these severe droughts are unmatched in duration, and possibly in severity, by any of the droughts of the instrumental period and therefore, we refer to them hereafter as 'monsoon megadroughts' (MMDs).

It is now evident that the MMDs between the mid 14th and 15th centuries were not confined to India. They are clearly apparent in a speleothem $\delta^{18}O$ record from Wanxiang Cave (33 °N, 105 °E) in central China (Zhang et al., 2008) and from a tree-ring-based Palmer Drought Severity Index (PDSI) record from Bidoup Nui Ba National Park (BDNP; 11 °N, 110 °E) in southern Vietnam (Buckley et al., 2010) (Fig. 4). In addition, historical accounts and archaeological studies suggest that these MMDs may have also occurred in Sri Lanka (Thera, 1967). Although the relationship between climate and societal change is complex and not necessarily deterministic, the widespread societal changes across monsoon Asia between the mid 13th to 15th centuries, which include famines and significant political reorganization within India (Dando, 1980; Pant et al., 1993; Maharatna, 1996), the collapse of the Yuan dynasty in China (Zhang et al., 2008); Rajarata civilization in Sri Lanka (Indrapala, 1971), and the Khmer civilization of Angkor Wat fame in Cambodia (Buckley et al., 2010), strongly suggest that the MMDs may have played a major contributing role in shaping these societal changes. Recent historical and archaeological data from western Tibet also appear to support the inference that MMDs had a significant effect on the people and polities of the region. From ca 950 to 1350 AD, western Tibet was dominated by three polities—Purang, Guge, and Maryul—which formed a confederacy ruled from Purang (Vitali, 1996; Petech, 1997; Aldenderfer and Zhang, 2004). It dominated trade, became wealthy, and was responsible for the establishment of numerous new Buddhist monastic and temple institutions. After 1200 AD however, the polity began a slow decline, and by ca AD 1350, it had collapsed. Although the historical documents describe this collapse in primarily political terms, other evidence points to significant environmental deterioration. Repeated famines (Vitali, 1996: 374), foreign invasions, and political subordination by outsiders characterize the region from AD 1250–1350. Other documents point to refugees passing through the region from the east, west, and south (Petech, 1997). Tibetan-speaking peoples apparently fled the plateau in large numbers in search of food after constant crop failure, with some traveling as far south as the Kathmandu Valley (Charles Ramble, personal communication to Mark Aldenderfer, 2009). Archaeological evidence from the Sutlej Valley near the former Guge capitol of Tsaparang provide evidence of village abandonment, which was apparently caused by a significant drop in the water table that left stranded major irrigation systems upon which these villages depended. At some field systems, the water table dropped more than 1 m. These abandonments are tentatively dated to the period AD 1250–1300 (unpublished data), which corresponds with the timing of the late 13th century MMD in India.

Emerging tree-ring-based reconstructions of the Indian and SE Asian monsoon variability spanning the more recent centuries from northwestern Thailand (Buckley et al., 2007), northern Vietnam

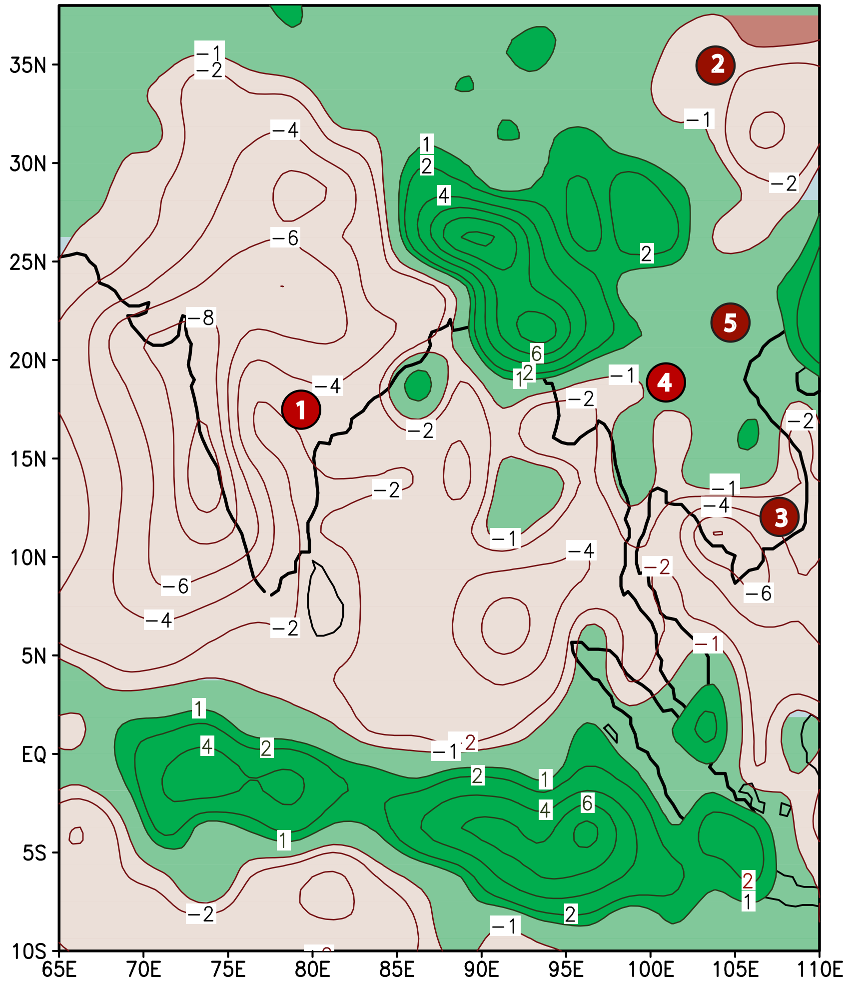

Fig. 3. Map showing locations of the key Asian Monsoon sites mentioned in the text. Contours and shading indicate composite precipitation anomalies (mm/day) during the major monsoon break spells in AD 2002 and 2004. The rainfall data are from the Climate Prediction Center Merged Analysis of Precipitation (CMAP)(http://www.esrl.noaa.gov/psd/data/gridded/data.cmap.html). Note decreased precipitation over the Indian sub-continent and SE Asia and increased precipitation south of the equator in the Indian Ocean and over the North Bay of Bengal, Bangladesh, and Northeast India. Also shown are locations of sites where the proxy data suggest prominent MMDs between AD 1250 and 1800. MMDs during the mid 14th to 15th centuries are documented in speleothem records from Dandak (1) (Sinha et al., 2007) and Wanxiang (2) (Zhang et al., 2008) Caves and in a tree ring record from Bidoup Nui Ba National Park (BDNP) (3) in southern Vietnam (Buckley et al., 2010). Additional instances of MMDs in the subsequent centuries are provided by tree ring reconstructions from Thailand (4) (Buckley et al., 2007), and northern Vietnam (5) Sano et al., 2009) (for interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

(Sano et al., 2009), and southern India (Borgaonkar et al., 2010) illuminate two additional episodes of monsoon megadroughts during the 17th and mid 18th centuries (Fig. 5). The latter MMD, in particular, is well-documented across monsoon Asia, and coincides with the collapse of all the major kingdoms in Southeast Asia (Leiberman, 2003; Cook et al., 2010). The spatio-temporal pattern of the aforementioned droughts are corroborated by a recent seasonally resolved gridded spatial reconstruction of Asian monsoon drought and pluvials over the past millennium, which is derived from a network of tree-ring chronologies from monsoon Asia (Cook et al., 2010). On the basis of these reconstructions, together with speleothem-based late Holocene reconstructions of monsoon variability from India (Sinha et al., 2007) and China (Zhang et al., 2008), it appears that there were at least five episodes of MMDs during the LIA (nominally, AD 1350–1850) and furthermore, four of these five episodes occurred within a period of generally reduced monsoon strength in Asia between AD 1300 and 1700, as shown previously in a number of studies (Anderson et al., 2002; Fleitmann et al., 2004, 2007; Wang et al., 2005; Hu et al., 2008)(Fig. 5).

The case for repeated occurrences of MMDs identified in several high fidelity monsoon reconstructions across widely separated regions from monsoon Asia is sufficiently compelling to suggest that monsoon circulation can *lock* into a drought-prone mode that may last for years to decades. Understanding what climate dynamics triggered and sustained such extended periods of drought is important in order to anticipate the likelihood of their reoccurrence today. As briefly mentioned before, the instrumental record from India points to ENSO (e.g., Kumar et al., 2006) and intra-seasonal oscillations in the CTCZ (e.g., Krishnan et al., 2003) as two important and potentially independent mechanisms for monsoon failure. Changes in radiative forcing associated with solar flux variability, explosive volcanisms (e.g., Fan et al., 2009), and aerosols (e.g., Meehl et al., 2008) may provide additional external mechanisms that could trigger and sustain the drought-inducing modes on inter-annual to decadal timescales.

One of the key objectives of this paper is to outline evidence from the proxy records that provide constraints on the spatial extent and severity of the MMDs. We explore key teleconnection patterns between the monsoon and other parts of the climate

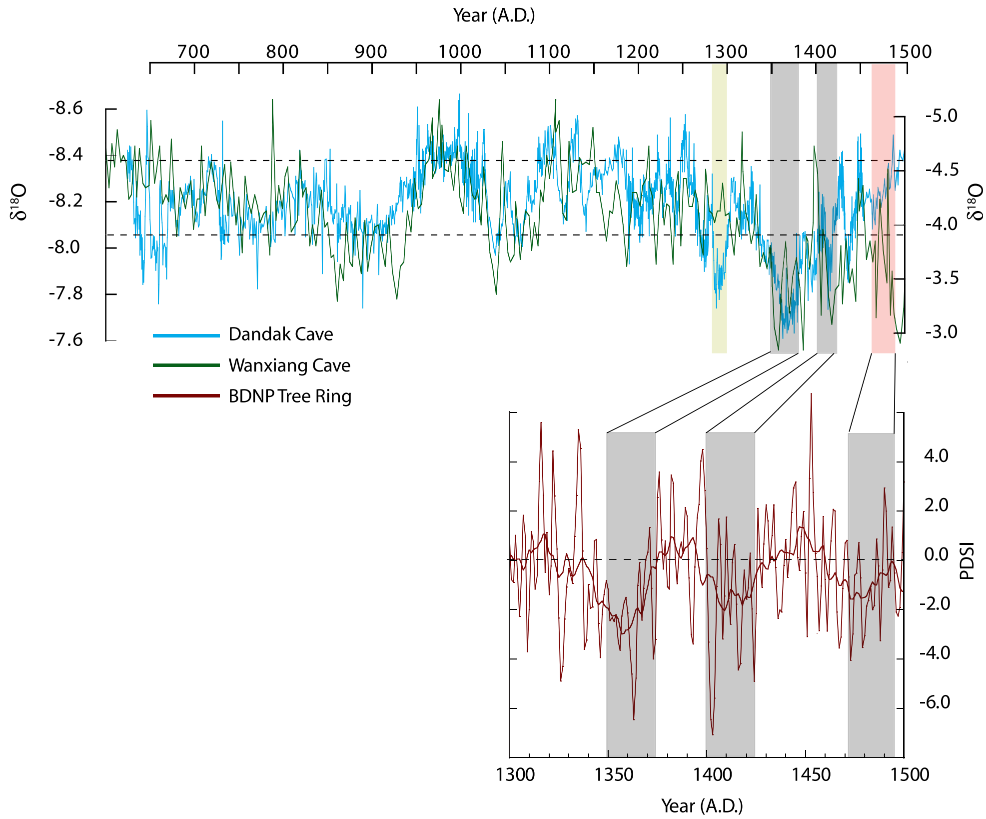

Fig. 4. Comparison of proxy records that show prominent MMDs in monsoon Asia. (Top) Comparison of the speleothem raw $\delta^{18}O$ data from Dandak Cave (Sinha et al., 2007; Berkelhammer et al., 2010) and Wanxiang Cave (Zhang et al., 2008). (Note that vertical axes for speleothem records are inverted to show that drier conditions are down). (Bottom) Tree ring-width based PDSI reconstruction from Bidoup Nui-Ba National Park (BDNP) in southern Vietnam (Buckley et al., 2010) between AD 1300 and 1500. Thick line is a 15-year running average. The MMDs in all three records are shown with shaded bars. The late 13th century MMD in India (light yellow bar) is not evident in other two records while the late 15th MMD (pink bar) is only observed in the Wanxiang Cave and BDNP tree ring records (for interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

system by using key high-resolution and well-dated proxy records (Fig. 6), many of which have become available only recently, to seek dynamical explanations for their occurrence during the LIA. Our analysis is informed by an emerging view of the monsoon, which considers it as a manifestation of the seasonal migration of the ITCZ and hence, the climate system of global scale (Sikka, 1980; Chao, 2000; Chao and Chen, 2001; Trenberth et al., 2000; Gadgil, 2003; Srinivasan and Joshi, 2007; Wang, 2009; Boos and Kuang, 2010). In this view, the regional monsoons of Asia (e.g., Indian, SE Asian, and East Asian) are interactive components of a singular ‘global monsoon’ characterized by seasonal overturning of the atmosphere in the tropical and sub-tropical latitudes which generate strong seasonal contrasts in precipitation (Trenberth et al., 2000). Although, a land–sea thermal contrast undoubtedly plays an important role in influencing regional monsoon circulations of Asia, it is however, not critical for its existence or its year-to-year variability (Gadgil, 2003; Hoyos and Webster, 2007; Cane, 2010).

2. Dandak Cave $\delta^{18}O$ record

Results from the Dandak Cave speleothem (DAN-D) $\delta^{18}O$ record (Fig. 2a) were published by Sinha et al. (2007) and additional high-resolution $\delta^{18}O$ measurements were reported by Berkelhammer et al. (2010). The cave’s location and its micro-climate, local surface climate, sample description, and methods describing the sampling protocol for the $\delta^{18}O$ and ^{230}Th analyses are described by Sinha et al. (2007). The $\delta^{18}O$ data in this paper are presented on the age model reported by Berkelhammer et al. (2010). We have previously shown that the $\delta^{18}O$ changes primarily reflect variations in the regional rainfall amount (Sinha et al., 2007). This is based on the following observations: 1) Century-long instrumental rainfall records from three meteorological stations near Dandak Cave correlate strongly with the CMZ rainfall and the AIR (Figs. S1 and S2) (Rajeevan et al., 2010). 2) Isotopic data from the Global Network of Isotopes in Precipitation (GNIP) database (Bowen and Revenaugh, 2003 [http://waterisotopes.org]) and a regional calibration study (Yadava, 2002) provide evidence for a strong inverse relationship between the $\delta^{18}O$ of precipitation and monsoon rainfall amounts (Sinha et al., 2007; Berkelhammer et al., 2010). 3) The empirically observed $\delta^{18}O$-precipitation-amount slope ($\Delta\delta^{18}O-\Delta P$) is similar to that obtained from an isotope-enabled Atmosphere General Circulation Model (AGCM) simulation, which is nudged to historical reanalysis fields (Fig. S5) (Yoshimura et al., 2008). 4) Experiments with an AGCM fitted with isotope tracers show a significant negative relationship between the $\delta^{18}O$ of precipitation and a vertical wind shear index, which is representative of the strength of monsoon circulation across the Indian sub-continent (Vuille et al., 2005). 5) The non-monsoonal rainfall (~10–20% of annual rainfall) at this site does not contribute substantially to recharge of groundwater or to the karst above the cave, and hence, to overall variations in the $\delta^{18}O$ of Dandak Cave record (Yadava, 2002; Sinha et al., 2007).

Precise delineation of droughts in the Dandak Cave $\delta^{18}O$ time series requires a quantitative understanding of how variations in monsoon rainfall amount influence the $\delta^{18}O$ of speleothem in

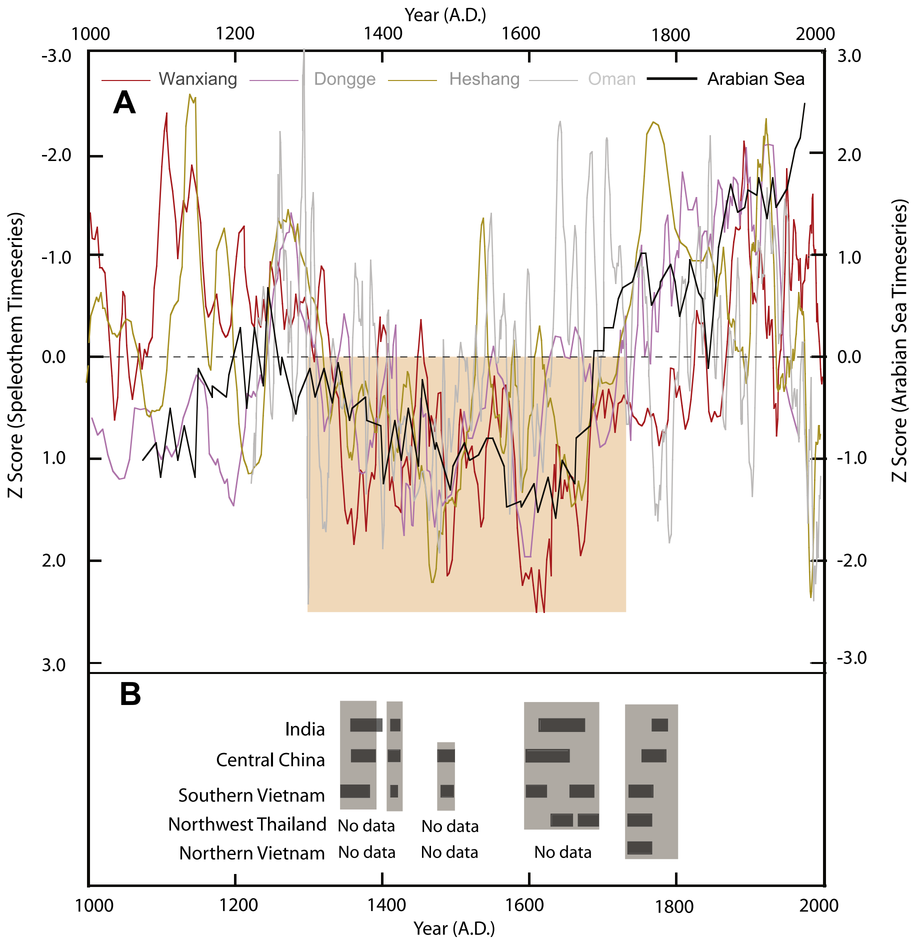

Fig. 5. (A) Low frequency behavior of the Asian Monsoon during the last millennium. Proxy-inferred monsoon histories during the past millennium (3–5 point smoothed and standardized by their own standard deviation) are from sites located within the core monsoon areas of Asia (top panel). The Arabian Sea time series is a proxy for the Indian monsoon circulation strength. Note the inverted vertical axis (drier condition is down) for all speleothem records. The interval between AD 1300 and 1700 is marked by general weakening of monsoon in all records (shaded box). (B) The bottom panel shows a schematic representations of spatio-temporal distribution of inferred MMD (lasting at least >10 years) as interpreted by authors of those studies (see text for more information). We broadly grouped the MMDs as inferred from the individual proxy records (dark shaded boxes) to fall within five discrete multidecadal length episodes of weaker monsoon (gray vertical bars) (for interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Dandak Cave. This is a challenging task considering that climate related variations in the $\delta^{18}O$ of speleothems during the late Holocene are not expected to be substantially larger than non-climate related processes unique to karst specific processes (Fairchild et al., 2006). Our effort to transfer stalagmite $\delta^{18}O$ values into paleo-rainfall amounts is hampered by the absence of a long-term $\Delta\delta^{18}O$–ΔP calibration data set and because the Dandak Cave $\delta^{18}O$ time series does not overlap with the available instrumental records. Despite these problems, there exist several lines of evidence that allow us to cast the $\delta^{18}O$ variations in Dandak Cave record in the context of 20th century monsoon rainfall variability. We generated a synthetic 20th century speleothem $\delta^{18}O$ time series for our study area based on known rainfall amounts and $\Delta\delta^{18}O$–ΔP derived from the IsoGSM isotope-enabled AGCM simulation (Fig. 2b), which provides the isotopic composition of surface water and atmospheric vapor at 6-hourly resolution on a $2.5 \times 2.5°$ global grid spanning AD 1979–2008. The Yoshimura et al. (2008) model employs 'nudging' – an approach where a fully functional GCM is corrected to the observed climatology using a prescribed spatial/spectral scale, which allows for a direct comparison between model output and measured climate and isotopic measurements on event timescales. Further details of the methodology used to generate the model outputs can be found in the original publication (Yoshimura et al., 2008) and the robustness of the results are described in their original publication as well as in subsequent work that utilized the model outputs (e.g., Uemura et al., 2008; Frankenberg et al., 2009). The $\Delta\delta^{18}O$–ΔP was obtained by regressing weighted mean $\delta^{18}O$ of June to September (JJAS) precipitation from the GCM simulation (Yoshimura et al., 2008) against the CMZ's JJAS rainfall amounts during the 30 years of the model simulation ($r = -0.54$, $p < 0.003$; Fig. S5). To estimate the uncertainty in this slope, we used a boot-strapping approach where we randomly selected 100 combinations of 20-year bins from the 30-year simulation and calculated the slope of the amount effect for each of these 20-year windows. The slope of the $\delta^{18}O$-precipitation-amount relationship was used to convert the variations in the CMZ's JJAS rainfall (AD 1901–2006) into the $\delta^{18}O$ of calcite precipitated in isotopic equilibrium at known temperature for Dandak Cave. The synthetic $\delta^{18}O$ series of speleothem calcite was adjusted to account for the observed $\sim 0.5‰$ enrichment in the $\delta^{18}O$ of drip water in Dandak Cave (Sinha et al., 2007) and was smoothed by a two year running average to mimic the mixing of meteoric waters in the overlying karst. We used a Monte Carlo simulation to generate 5000 possible 20th century calcite time series by perturbing the slope of the amount effect based on the uncertainty in this parameter from the boot-strapping exercise.

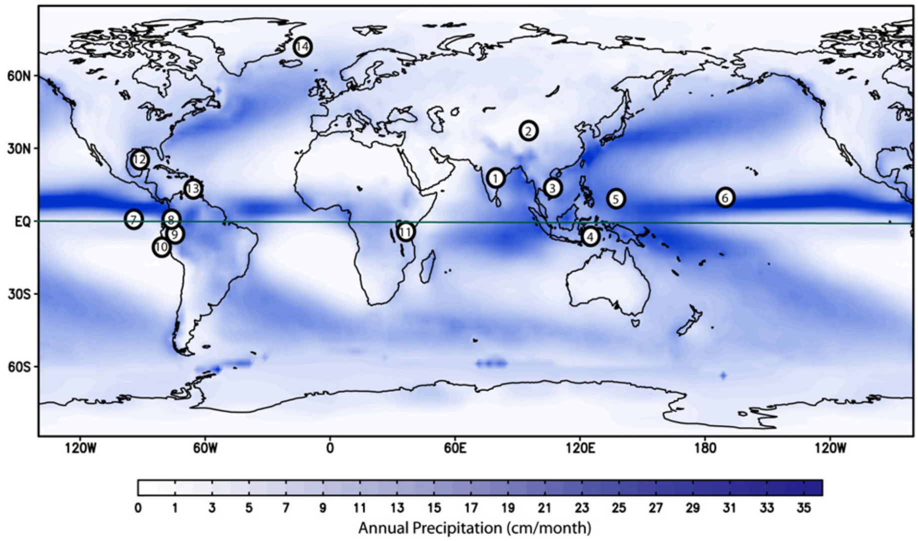

Fig. 6. Map of mean annual global precipitation (cm/month) with locations of proxy records discussed in this paper. 1, Dandak Cave (Sinha et al., 2007; this study); 2, Wanxiang Cave (Zhang et al., 2008); 3, Vietnam (Buckley et al., 2010); 4, Makassar Strait (Oppo et al., 2009; Tierney et al., 2009); 5 & 6 Palao and Washington Islands (Sachs et al., 2009); 7, El Junco Crater Lake on Galapagos Island (Conroy et al., 2008, 2009); 8, Ecuador (Moy et al., 2002); 9 Northeast Peru (Reuter et al., 2009); 10, Peruvian shelf (Rein et al., 2004); 11, Lake Naivasha (Verschuren et al., 2000); 12, Gulf of Mexico (Richey et al., 2007); 13, Cariaco Basin (Haug et al., 2001; Black et al., 2007); 14, Icelandic Shelf (Massé et al., 2008), & (Sicre et al., 2008). Precipitation data is from Legates/MSU precipitation climatology available from http://jisao.washington.edu/legates_msu/. Note the structure of the ITCZ in the eastern equatorial Indian Ocean/western Pacific (wide band) is different from the eastern Equatorial Pacific and Atlantic Ocean (narrower band of heavy precipitation).

The majority of the modeled speleothem $\delta^{18}O$ values during the 20th century fall within the range of measured $\delta^{18}O$ values (-4.0 to -4.5‰, $1\sigma = 0.21$‰, $n = 120$) of the modern calcite collected in Dandak Cave (e.g., soda straws, stalactites tip, flowstones top, and calcite precipitated on glass plates between AD 2000 and 2008). Additionally, the $\delta^{18}O$ data from the top 5–7 mm of another stalagmite from Dandak Cave, which contains an anomalous radiocarbon signal from thermonuclear testing in the 1950s (Yadava, 2002), documents a similar $\delta^{18}O$ range. A close similarity between the modeled and measured $\delta^{18}O$ data during the 20th century suggest that the magnitude and temporal duration of $\delta^{18}O$ variations in our synthetic time series can be used as a guide to quantitatively compare 20th century monsoon rainfall variability in the CMZ to pre-instrumental $\delta^{18}O$ variations in the Dandak Cave speleothem record. We identify three positive isotopic anomalies during AD 1901–03, 1965–68 and 1985–88, as intervals when the JJAS rainfall in the CMZ was 10% below the modern average in two out of three consecutive monsoon seasons (Fig. 2b).

Converting the Dandak stalagmite $\delta^{18}O$ record into a quantitative assessment of past rainfall amount using this approach includes uncertainties associated with other environmental variables such as changes in cave temperature, local evaporation, and ambient relative humidity. However, these factors tend to shift the $\delta^{18}O$ values in the same direction as the amount effect, and therefore, would not change the interpretation of $\delta^{18}O$ variations in Dandak Cave record as one of regional monsoon strength (Sinha et al., 2007). We infer intervals of droughts in the Dandak record delineated by $\delta^{18}O$ values that are higher than -3.8‰, which is equivalent to a $\sim$10% reduction (with respect to the 20th century mean) in monsoon rainfall. We further delineate 'megadrought' as those intervals associated with $\delta^{18}O$ values above -3.3‰, which is equivalent to a 20% reduction in monsoon rainfall. Using this criterion, megadroughts documented in the Dandak record persisted for 5–30 years (Fig. 2a). These estimates are similar to those estimated from tree-ring width records from sites in southern Vietnam (Buckley et al., 2010). Although extreme reductions in monsoon rainfall (i.e., >20% below mean) in the CMZ have occurred during the instrumental interval (see Fig. 1), none of the modern droughts come close to lasting as long as these pre-instrumental MMDs.

3. Proxy data comparison and discussion

In the following sections, we attempt to provide dynamical explanations of MMDs by exploring key teleconnection patterns between the monsoon and other parts of the climate system. This is done by using select high-resolution and well-dated proxy records from across the globe (Fig. 6). We evaluate proxy records to seek clear evidence for sustained and large-scale perturbations in key ocean-properties such as the ENSO state and the ITCZ position – the two leading modes of ocean–atmosphere variability that are known to influence monsoon circulation and precipitation patterns on inter-annual to decadal timescales.

3.1. Tropical Pacific – monsoon megadrought link

Tropical Pacific sea surface temperature (SST) anomalies associated with ENSO events represent one of the most important modulators of Indian monsoon rainfall on an inter-annual timescale (Kumar et al., 2006). During an El-Niño event, the locus of deep atmospheric convection shifts eastward from the Indo-Pacific Warm Pool (IPWP) to the central or eastern Pacific. This shift induces low-level convergence over the eastern equatorial Indian Ocean (EEIO) that drives anomalous Walker circulation whose descending limb is centered over the Indian sub-continent, thus suppressing ascent and convection-driven monsoon rainfall (Rasmussen and Carpenter, 1982; Nigam, 1994). Comparison of the AIR with SSTs from the Niño 3 region reveals that years with warm tropical Pacific SST anomalies, particularly when centered over the central equatorial Pacific, are generally associated with severe monsoon drought (Kumar et al., 2006). Indeed, some of the most devastating droughts in India and SE Asia occurred in association with extreme El-Niño events during the historic (Grove, 1998) and instrumental periods (Kumar et al., 2002). Nonetheless, large departures in monsoon rainfall in the Indian sub-continent (magnitude greater than one standard deviation from the mean)

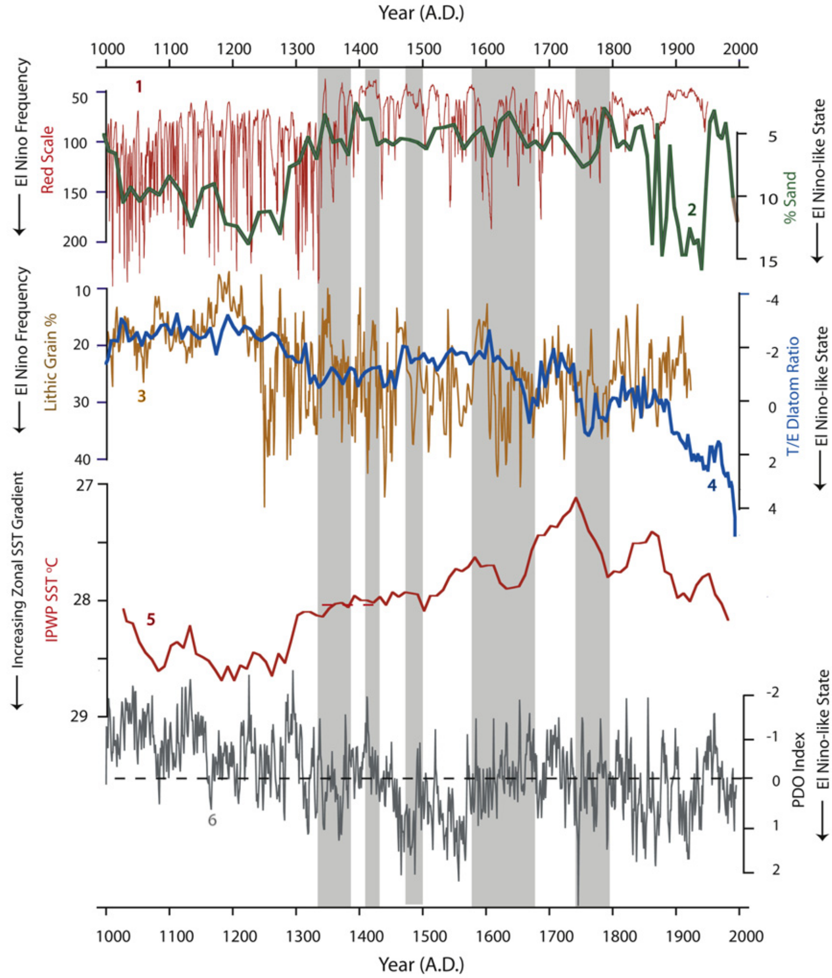

Fig. 7. Stacked time series showing proxy records of ENSO during the past millennium (color coded). The records from top to bottom are (1) Laguna Pallacocheha red color intensity record from Ecuador (Moy et al., 2002); (2) % sand from El Junco Crater Lake in Galapagos Island (Conroy et al., 2008), (3) lithic grain % in a marine core off Peru (Rein et al., 2004); (4) diatom abundance from El Junco Crater Lake in Galapagos Island (Conroy et al., 2009); (5) Mg/Ca based SST reconstruction from the Makassar Strait, IPWP (Oppo et al., 2009); (6) tree ring based PDO reconstruction (MacDonald and Case, 2005). Vertical gray bars broadly represent temporal duration of MMDs as delineated in Fig. 5 (for interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

have also occurred in the absence of El Niño. In fact, of the 22 large droughts in India that occurred during AD 1871–2002, only 11 were associated with El Niño (Kumar et al., 2002). The inverse monsoon–ENSO relationship is thus non-stationary and appears to have weakened considerably since the 1980s (Kumar et al., 1999).

To assess the role that ENSO dynamics may have played in causing the MMDs, we compare a series of proxy records taken directly from the ENSO region or from locations that are significantly affected by the ENSO through teleconnection patterns (Fig. 7). These proxy records have been interpreted by their authors to reflect changes in El-Niño frequency or the mean state of ENSO in the tropical Pacific. The first two records in Fig. 7 are sediment records from Laguna Pallacochocha in Ecuador (Moy et al., 2002) and El Junco Crater Lake on the Galapagos Islands (Conroy et al., 2008). These time series' record changes in fluvial discharge associated with enhanced El-Niño precipitation events. Both records show a sharp reduction in the frequency of El-Niño events coincident with the first and perhaps the most severe episode of MMDs. These same lake records also indicate that there was a shift towards decreased El-Niño frequency during the subsequent episodes of MMD. Both tropical Pacific records imply cooler conditions in the eastern tropical Pacific, and are consistent with coral $\delta^{18}O$ based SST estimates during AD 1320–1462 from the Palmyra Atoll in the central Pacific (Cobb et al., 2003), which suggests that peak drought conditions in monsoon Asia during the mid 14th–early 15th centuries occurred at a time that was characteristically more La-Niña-like[3] rather than El Niño-like.

Some studies have also suggested that the phase-locking of El-Niño events (without an implicit need for an increase in El-Niño frequency) during the warm phase of the Pacific Decadal Oscillation (PDO), the leading mode of multidecadal SST variability in the North Pacific (Gershunov and Barnett, 1998; Power et al., 1999; Salinger et al., 2001), can reinforce SST anomalies, resulting in persistent precipitation anomalies over the tropics and the monsoon region (Krishnan and Sugi, 2003; Buckley et al., 2007; Sano et al., 2009). This notion also finds support in a study by Meehl and Hu (2006), who conducted a 1360-yr long control run from a coupled climate model and simulated 'megadroughts' in the Indian monsoon and southwestern United States regions. The simulated megadroughts occur approximately once every 150 years and were the result of natural multidecadal SST variability in the

[3] We use the term(s) El Niño-like (La-Niña-like) to refer to a spatial SST pattern and a reduced (increased) time-mean zonal SST gradient along the equatorial Pacific, which are typical of individual El Niño (La-Niña) events.

Indian and Pacific Oceans. Analysis of the model variability shows that the mechanisms involved in producing megadroughts share some common elements with various ENSO processes. To assess the possibility of this mechanism, we examine a 1000-year tree ring-based reconstruction of the PDO (MacDonald and Case, 2005). The PDO was generally neutral or more La-Niña-like during each of the MMD intervals. There is a shift towards El Niño-like conditions during the latter part of the 15th century and again during the latter half of the 16th century. The earlier interval corresponds to one of the MMD episodes but the latter interval occurred at a time where we find no evidence of severe and sustained droughts in the monsoon proxy records. Furthermore, there is a lack of characteristic 50–100 year periodicity in this reconstruction between AD 1600 and 1800 (MacDonald and Case, 2005), which is an interval that encompasses the last two MMD episodes (Fig. 7).

In contrast to evidence presented above, a survey of other proxy ENSO reconstructions however, supports the role of El Niño as a potential driver of MMDs. For example, a record of variations in lithic materials from a marine core off the Peruvian coast (Rein et al., 2004), which is interpreted to reflect El-Niño related flood events in western Peru, suggest a small but measurable increase in El-Niño frequency just prior to the onset of the first MMD episode (Fig. 7). A similar conclusion about the ENSO mean state can be made based on changes in the relative abundance of tychoplanktonic to epiphytic diatoms from a sediment core in the Galapagos Islands in the eastern Equatorial Pacific (EEP) that reflect lake level, local and regional SSTs, convection, and precipitation, all of which tend to increase during individual El-Niño events (Conroy et al., 2008, 2009). Both of the records suggest that the transition to increased El-Niño frequency and protracted El Niño-like mean state were sustained through the entire interval in which several episodes of MMDs occurred. Comparison of the diatom inferred SST record with a direct SST reconstruction from IPWP, the latter derived from Mg/Ca thermometry of surface dwelling planktonic foraminifera from Makassar Strait in Indonesia, is also shown in Fig. 7 (Oppo et al., 2009). These two records indicate that the equatorial zonal SST gradient between the IPWP and EEP was steepest during AD 1000–1250 and then declined rapidly between AD 1250 and 1300 (also see Fig. 1 in Conroy et al., 2010). The SST gradient remained stable for the next three hundred years and then declined further through much of the 17th century. Since the late 17th century, there has been a gradual recovery in the SST gradient (Conroy et al., 2010). When interpreted in an ENSO context, the higher (lower) zonal SST gradient before (after) AD 1250 implies a La-Niña-like (El Niño-like) state in the tropical Pacific. This observation is supported by apparent similarity in timing of occurrence of some of the MMDs with the high stands in Lake Naivasha in the eastern equatorial Africa (EEA) (Verschuren et al., 2000). Today, the precipitation pattern in EEA exhibits a positive association with warm SST anomalies in the western IO, which tends to occur during El-Niño events (Nicholson and Entekhabi, 1987; Nicholson and Kim, 1997; Nicholson, 2000) which points to dominantly El Niño-like conditions at times of drier conditions over monsoon Asia.

It is difficult to reconcile the apparent discrepancy amongst the various tropical Pacific and ENSO proxy reconstructions that span the last millennium. One subset of records suggests La-Niña-like conditions persisted at times of megadrought over Asia (Moy et al., 2002; MacDonald and Case, 2005; Conroy et al., 2008), while another subset suggests the opposite (Rein et al., 2004; Conroy et al., 2009; Oppo et al., 2009). Each of these ENSO proxy reconstructions also suffers from uncertainties associated with how robust the scaling is between ENSO and hydrologic conditions over the tropical Pacific. It appears to us that at present, there is simply too much disagreement amongst the proxy reconstructions of ENSO to conclude that El Niño-like or La-Niña-like conditions were predominant during times of MMD. Furthermore, we also did not find a temporally consistent relationship between intervals of MMD and intervals of reduced solar flux or increased volcanic forcing-factors that could have influenced El-Niño SST anomalies through the so called 'Ocean Thermostat' mechanism as observed in simulations with the Zebiak–Cane model of tropical Pacific coupled ocean–atmosphere dynamics (Zebiak and Cane, 1987; Clement et al., 1996; Mann et al., 2005). Thus, in summary, we do not find sufficient justification for calling upon ENSO as the causative forcing that brought about the MMDs. However we note with interest that a number of recent studies suggest an unusual distribution of SST anomalies, which is composed of anomalous warming in the tropical central Pacific flanked by colder than normal SST to the east and west – a pattern referred to as El-Niño Modoki (Ashok et al., 2007; Yeh et al., 2009; Kug et al., 2009), has a particularly strong teleconnection with the Indian monsoon rainfall (Kumar et al., 2006). Were the MMDs in India/Asia linked to more frequent occurrences of ENSO Modoki-like conditions during the last millennium? The current suite of proxy records of SST from the tropical Pacific however, lack the necessary spatial and temporal details to definitively assess this intriguing possibility.

3.2. *Global monsoon – ITCZ – monsoon megadroughts*

For more than three hundred years, the monsoon circulation has been viewed as an overturning circulation analogous to a thermally-driven sea breeze on a continental scale (Wang, 2009). This conventional view of the monsoon is now being challenged by a rapidly emerging body of observational and modeling data that considers regional monsoons to be a manifestation of the seasonal migration of the ITCZ and henceforth, a climate system behavior at a global scale (Chao, 2000; Trenberth, 2000; Chao and Chen, 2001; Gadgil, 2003; Wang, 2009). In this view, the regional monsoons are interactive components of a singular 'global monsoon' system that is characterized by seasonal overturning of the atmosphere in the tropical and sub-tropical latitudes of both hemispheres that is accompanied by seasonal precipitation changes (Trenberth et al., 2000). When viewed in this framework, variations in regional monsoon circulation and precipitation in both hemispheres are intrinsically tied to modulations in the dynamics of the ITCZ from intra-seasonal (e.g., active break cycle of monsoon) to orbital timescales (e.g., precessionally forced changes in the ITCZ mean position). The aforementioned discussion however, frames the global monsoon-ITCZ relationship in the broadest sense only. The ITCZ behavior, at both local and regional scales, can be quite complex (Tomas and Webster, 1997; Webster et al., 1998; Tomas et al., 1999). These studies highlight the role of cross-equatorial sea level pressures, SST gradients, and inertial instabilities in determining the location and strength of equatorial convections.

The global monsoon-ITCZ link is perhaps best illustrated on the centennial to millennial scale variability of this system as documented in proxy reconstructions of the monsoons in eastern China (Wang et al., 2001, 2008), southern China (Dykoski et al., 2005; Wang et al. 2005, Yuan et al., 2004; Cheng et al., 2006), India (Sinha et al., 2005), the IO (Overpeck et al., 1996; Schulz et al., 1998; Burns et al., 2003; Gupta et al., 2003; Fleitmann et al., 2003, 2007), South America (Wang et al., 2004, 2006; Cruz et al., 2005), Southwest United States (Asmerom et al., 2010), and Africa (Weldeab et al., 2007). These studies document an asymmetric response of monsoon precipitation associated with a weaker (stronger) monsoon circulation in the northern (southern) hemispheres, when the ITCZ is shifted more to the south (to the north) (Cheng et al., 2009). The millennial scale variations in the mean latitudinal migrations of the ITCZ are thought to be driven by the

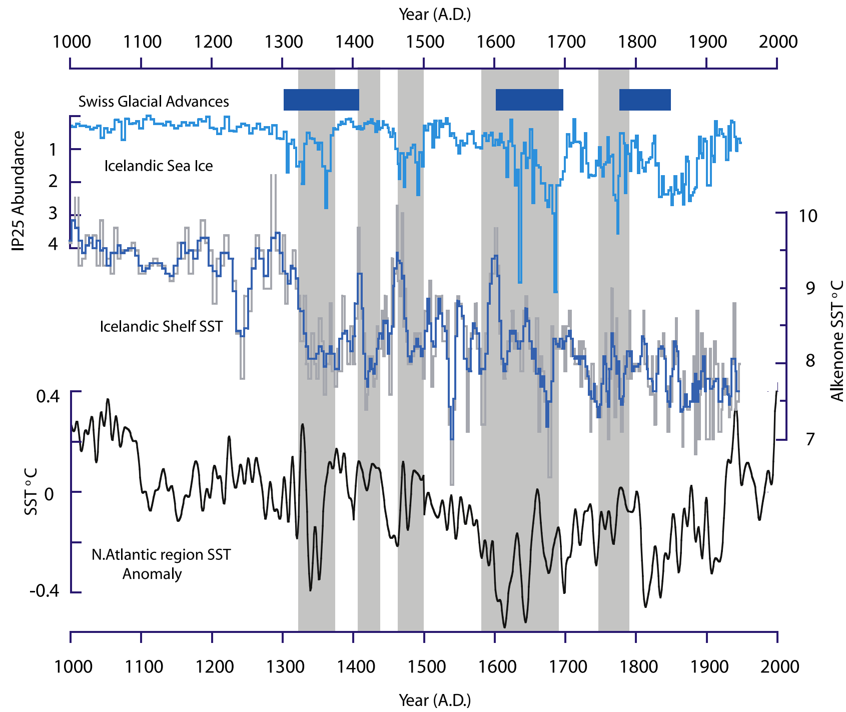

Fig. 8. Stacked time series of proxy records of temperature from the extratropical latitudes in the Northern Hemisphere (color coded). The records from top to bottom are temporal duration of Swiss glacial advances (Holzhauser et al., 2005), biomarker based sea ice reconstruction (Massé et al., 2008), Icelandic shelf SST (Sicre et al., 2008) and a composite SST estimate from the Atlantic region (Mann et al., 2009). Vertical gray bars represent temporal duration of MMDs as delineated in Fig. 5 (for interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

inter-hemispheric temperature gradient that is forced by modulations in northward heat transport between the tropics to extratropics via the ocean (e.g., Delworth and Mann, 2000; Knight et al., 2005). Results from North Atlantic freshwater 'hosing' simulations (e.g., Vellinga and Wood, 2002; Zhang and Delworth, 2005) as well as simulations with enhanced sea or land ice cover centered over the high northern latitudes (e.g., Chiang and Bitz, 2005; Broccoli et al., 2006), suggest that cooler temperature anomalies in the extratropical latitudes are propagated southward through the wind-evaporation-SST feedback (Chiang and Bitz, 2005), which intensifies the NE trade winds in the Atlantic and Pacific Basins, and pushes the cold SST front further southward, eventually creating a dipole temperature anomaly around the Equator that forces a southward shift of the ITCZ in all three ocean basins (Chiang and Bitz, 2005; Broccoli et al., 2006). The ITCZ displacement transports moisture away from the colder and drier hemisphere into the other hemisphere, resulting in a pronounced hemispheric asymmetric response in precipitation in tropical and monsoonal regions. Furthermore, a southward shifted ITCZ in some climate model simulations leads to intensification of the ENSO variability through attenuation of the annual cycle in the equatorial Pacific (e.g., Timmermann et al., 2007). Considering that the mean state of the monsoon itself can be substantially suppressed by a southward shifted ITCZ, increased ENSO variability may further serve to weaken the monsoon in Asia (Zhang and Delworth, 2005; Lu et al., 2006).

The millennial scale pattern of global climate variability during the last glacial interval conforms remarkably well to climate model projections-particularly with respect to the temporal synchrony of a hemispherically asymmetric response of the monsoon system that accompanied the large-scale temperature fluctuations documented in the Greenland ice cores (Wang et al., 2008). Can similar climate processes, albeit with forcing scaled to late Holocene boundary conditions, be called upon to explain discrete multidecadal to century-length intervals of weaker monsoon that contained the MMDs during the LIA? To assess this possibility, we compiled a suite of key proxy records of temperature from extratropical latitudes as well as those sensitive to the position of the ITCZ. In Fig. 8, we show an alkenone thermometry based summer SST record from the North Icelandic shelf (Sicre et al., 2008), whose chronology is constrained by historically dated tephra layers. The Icelandic shelf SST reconstruction is supported by a proxy reconstruction of the Icelandic sea ice, which was assessed from the same marine core, by examining changes in the relative abundance of IP_{25}, a biomarker produced by diatoms living in the sea ice (Massé et al., 2008). The biomarker record of sea ice compliments the previously available sea ice reconstructions based on historical accounts from this region (Ogilvie, 1984, 1991). We also illustrate the temporal duration and peak frontal positions of Swiss Alpine glaciers (Holzhauser et al., 2005) and a recent composite reconstruction of SST anomalies from the north Atlantic region (Mann et al., 2009) (Fig. 8).

Remarkably, all major episodes of the Swiss glacial advances are matched in timing by pulses of sea ice expansion and with prominent multidecadal length cold SST excursions in the Atlantic region composite SST record (Fig. 8). The Icelandic shelf SST reconstruction indicates an abrupt transition to colder SSTs in the mid 14th century, which is followed by a progressively cooler trend. Nearly all episodes of cold extratropical events indicated by these proxy records occurred in close temporal association with episodes of MMDs. These correlations are particularly compelling during the mid 14th, late 15th, and mid 17th centuries. These cold events in extratropical latitudes also appear to have occurred in synchrony with southward shifts of the ITCZ in the Atlantic Ocean and perhaps in the Pacific Ocean as well (Fig. 9). A record of increased (decreased) abundance of planktonic foraminifera *Globigerinoides sacculifer* in a marine core from the Gulf of Mexico reflect seasonal influx of Caribbean surface waters, the extent of

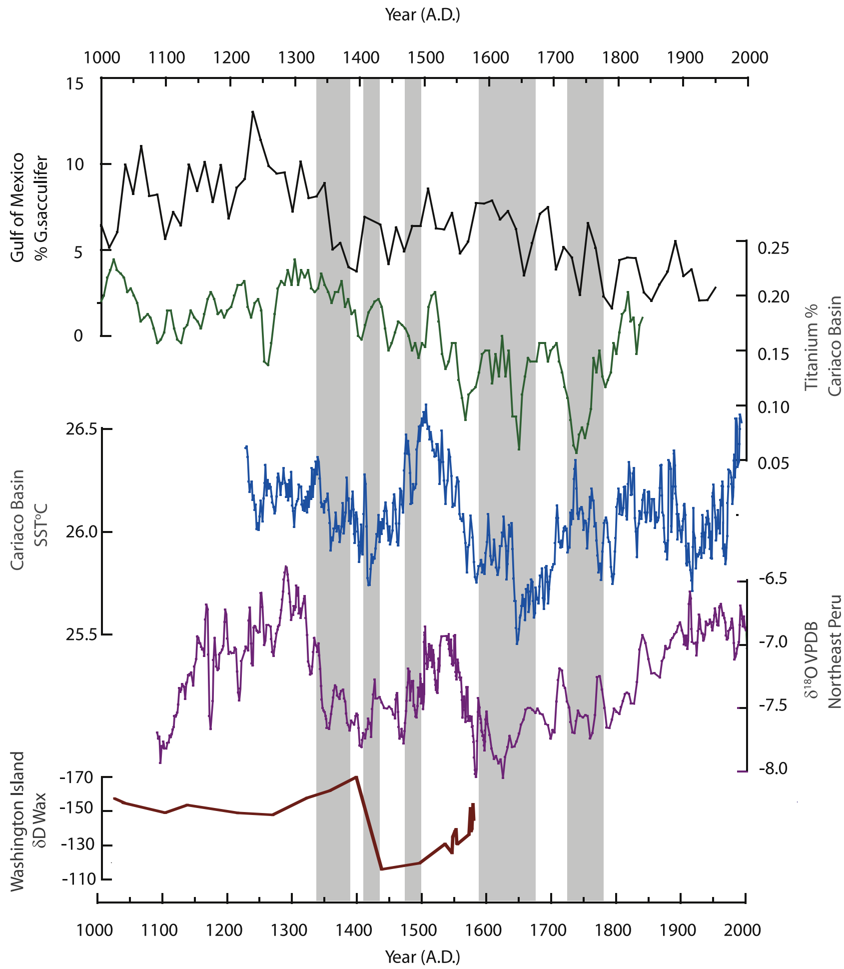

Fig. 9. Proxy indicators of the ITCZ behavior during the last millennium. The records from top to bottom are the Gulf of Mexico foraminiferal abundance (Richey et al., 2007); % titanium from the Cariaco Basin (Haug et al., 2001); Mg/Ca based SST reconstructions from the Cariaco Basin (Black et al., 2007); speleothem based precipitation reconstruction from the Northeast Peru (Reuter et al., 2009) and hydrogen isotopic record from the Washington Island in central tropical Pacific (Sachs et al., 2009). Vertical gray bars represent temporal duration of MMDs as delineated in Fig. 5 (for interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

which is influenced by the seasonal position of the ITCZ (Poore et al., 2004; Richey et al., 2007). A prominent feature of this record is an abrupt shift to lower abundance of foraminifera between AD 1300 and 1400 signaling a long-term trend to progressive more southward position of the ITCZ. The Gulf of Mexico record is closely matched by a record of variations in titanium concentration from the Cariaco Basin, which reflect the ITCZ related variations in precipitation over northern Venezuela (Haug et al., 2001). Lower concentrations of titanium imply a southward shifted ITCZ, reduced precipitation over coastal Venezuela, and consequently, decreased riverine flux to the Cariaco Basin. Taken together, these two proxy records illustrate a general southward trend in the ITCZ since AD 1300, which was punctuated by several prominent multidecadal to centennial scale episodes of even greater southward shifts. Some of these shifts e.g., during the mid 14th and mid 17th centuries, occurred in striking temporal synchrony with the MMDs. This assertion is corroborated by a high-resolution spring time SST record from the Cariaco Basin (Black et al., 2007) and a speleothem based precipitation record from northeast Peru, showing cooler tropical SSTs and wetter conditions in northeast Peru, both of which largely reflect the ITCZ behavior during the LIA (Reuter et al., 2009) (Fig. 9).

Proxy records of variations in the mean location of the ITCZ from the Pacific and Indian Oceans spanning the last 1000 years are rare. In one recent study, molecular and hydrogen isotopic variations in lake sediments from Washington Island, Galapagos, and Palau in the equatorial Pacific indicate that the ITCZ position in the Pacific shifted abruptly southward of its modern position during the onset of the LIA (Fig. 9) and remained southward till the mid 19th century (Sachs et al., 2009). Additional evidence for a southward shifted ITCZ during the LIA in the western equatorial Pacific are provided by the estimates of the sea surface salinity (SSS) (Newton et al., 2006; Oppo et al., 2009) and hydrogen isotopic composition of terrestrial plant wax (Tierney et al., 2009) in marine sediments from a site about 5 °S of the equator in the IPWP. The LIA interval in these records is marked by lower salinity (Newton et al., 2006; Oppo et al., 2009) and depleted isotopic values (Tierney et al., 2009) implying greater precipitation associated with closer proximity to the mean annual location of the ITCZ in this region. Furthermore, on multidecadal to centennial timescales, the SSS and isotopic variations spanning the last two millennia from this site are inversely correlated with the strength of the Indian and Asian monsoon rainfall implying an antiphase behavior in rainfall patterns between monsoon Asia and southern tropical Pacific (Oppo et al., 2009). Interestingly, this correlation persists even during the instrumental period as well (Fig. 4 in Oppo et al., 2009). Thus, on the basis of these proxy records, the southward bias of the ITCZ in the western equatorial Pacific (and in eastern Equatorial Indian Ocean) is consistent with the southward shifted ITCZ in the Atlantic sector.

Our review of the proxy data as illustrated in Figs. 8 and 9 link cooler conditions in the extratropical northern latitudes with a southward bias in the seasonal migration of the ITCZ and weaker regional monsoons over Asia (e.g., Fig. 5) during the LIA. These observations are consistent with results from other studies (Verschuren et al., 2000; Hodell et al., 2005; Lund et al., 2006). However, our synthesis, which utilizes recent well-dated proxy records of sea ice and SST from the Icelandic shelf, also highlights the presence of discrete multidecadal length cool events centered in the extratropics that correlate remarkably well (within the margin of dating errors) with transient southward excursions of the ITCZ and with most intervals of weaker monsoon that contained the MMDs. But how do these correlations bear on causality of MMDs? – a central question that motivated this study. As mentioned earlier, in some climate simulations, a weakened Indian and Asian monsoon is a robust response to southward shifted ITCZ (Vellinga and Wood, 2002; Zhang and Delworth, 2005, 2006). However, the exact dynamical pathways through which such teleconnections are achieved are not clear. Furthermore, the boundary conditions specified in these model simulations (e.g., magnitude of freshwater hosing in the N. Atlantic) are not relevant to the late Holocene interval. In the following section, we synthesize observations from instrumental data and satellite based observations of synoptic scale climatology of the IO and offer insights into the dynamics that link shifts in the ITCZ during the LIA to MMDs.

3.3. Dynamical relationship between monsoon megadroughts and the ITCZ

The onset of the Indian monsoon season, when viewed in the framework of a global monsoon model, can be thought of as a rapid jump of the ITCZ from about 5 °S in the IO during the boreal winter to about 15 °N over the Indian sub-continent in boreal summer months (Sikka, 1980; Chao, 2000; Gadgil, 2003). The ITCZ over the Indian sub-continent or more appropriately the CTCZ is 'maintained' by superposition of a westward moving 10–20 day and northward moving 30–60 day oscillation in the convective systems, which form over the Bay of Bengal and the equatorial IO respectively (Annamalai and Slingo, 2001; Lawrence and Webster, 2002; Goswami, 2005; Goswami et al., 2006a). While synoptic scale systems generated over the surrounding oceans play a crucial role in maintaining the CTCZ over the land, there is also a negative component of this interaction. In some years, particularly during the months of July and August, the moisture convergence over the EEIO becomes stronger, the monsoon trough (a system of contiguous heat and moist convective lows) shifts northward, resulting in enhanced precipitation over northeast India and along the foothill of Himalayas (Fig. 3) at the expense of convection and precipitation over the CMZ (Ramamurthy, 1969; Krishnamurthy and Shukla, 2000). This see–saw activity in the CTCZ, described as 'active' and 'break' spells of monsoon rainfall over India (Sikka and Gadgil, 1980; Krishnan et al., 2000), has a large impact on monsoon's inter-annual variability (Fig. S4) (Webster et al., 1998; Lawrence and Webster, 2001; Goswami et al., 2006a).

A prolonged break spell invariably leads to major droughts in India with the droughts in 2000 and 2002 serving as prime examples (Krishnan et al., 2003; Krishnan et al., 2006). Krishnan et al. (2006) suggested that a positive feedback between low-level monsoon westerlies (which normally flow onto the Indian sub-continent during the monsoon season) and the sub-surface IO dynamics on intra-seasonal timescales can force prolonged monsoon-breaks. This coupling involves anomalous equator-ward shifts in the low-level monsoon westerly jet, which suppress upwelling in the EEIO and maintains anomalously warm SSTs and enhanced regional convection. Convection over the EEIO in turn, induces anomalous subsidence over the CMZ through the regional overturning circulation cell. The termination of this feedback may occur through processes that counter the warming tendency of the oceanic anomalies such as cloud-radiative effects associated with the enhanced convection over the EEIO and heat loss from the ocean due to increased latent heat release (Krishnan et al., 2006). Additionally, results from simulations with a high-resolution AGCM forced with climatological SSTs, suggest that internal feedbacks between monsoon and midlatitude interactions may further enhance drought conditions by prolonging the break spells (Krishnan et al., 2009). In this feedback, the suppressed monsoon convection over the land induces Rossby wave dispersion in the summertime sub-tropical westerlies, which establishes an anomalous quasi-stationary circulation pattern that extends across continental Eurasia in the middle and upper troposphere. The intrusion of the dry extratropical winds into northwest India further decreases convective instability, which in turn, weakens the monsoon flow (Krishnan et al., 2009).

The aforementioned discussion of the modern synoptic scale climatology highlights the bimodal nature of monsoon with distinctly different circulation and precipitation regimes on intra-seasonal timescale. Conceivably, conducive climatological conditions at inter-annual to decadal timescales may favor persistence of one mode over the other. We suggest that during the LIA, a general southward bias of the ITCZ in the IO weakened the 'active' mode of monsoon circulation by forcing the monsoonal winds to blow equator-ward. Additionally, weaker monsoonal circulation may also have resulted from a reduced upper troposphere meridional temperature gradient between Eurasia and the IO (Goswami et al., 2006b) or through weakening of surface thermal gradient between the Tibetan Plateau and the tropical IO (Feng and Hu, 2008). The positive feedback between the equator-ward monsoon winds and thermocline dynamics in the IO suppressed upwelling and enhanced convection over the EEIO during the boreal summer months. This "break-prone" climatology during the LIA was accentuated during the distinctly cooler events in the extratropical latitudes of the Northern Hemisphere, which forced the ITCZ further southward in the IO leading to a further increase in convection over the EEIO. Thus, a protracted 'locking' of monsoon circulation into this mode of synoptic scale climatology would have favored more frequent (or of longer duration) break spells over the continental landmass and may have been instrumental in causing the MMDs. Because the spatial patterns of precipitation and OLR anomalies during the extended break phase are associated with widespread decrease in monsoon rainfall across India and SE Asia (Krishnan et al., 2000), our proposed mechanism helps to explain the widespread spatial signatures of MMDs.

Since the end of the LIA, the mid 19th to 20th century monsoon variability in India appears to be dominated by the active mode of monsoon with sporadic occurrences of extended break-related droughts (Joseph et al., 2009). Similarly, the interval before the LIA (AD 950–1250) in Dandak and Wanxiang speleothem records, which corresponds to the Medieval Climate Anomaly (MCA; nominally, AD 950–1350), is characterized by generally stronger monsoon (Fig. 2). Stronger monsoon during the MCA may be associated with a protracted phase of the "active-dominated" mode of monsoon. This conjecture is supported by a high-resolution record of isotopic and dust ion variations from a Mt. Everest ice core, which suggests a predominantly active mode of monsoon between AD 1000 and 1400 (Kaspari et al., 2007). In contrast, a new speleothem $\delta^{18}O$ record from northeast India – a region which experiences higher monsoon rainfall due to northward shifted monsoon trough during the intra-seasonal break spells (Ramamurthy, 1969; Krishnamurthy and Shukla, 2000) (Fig. 3), indicate substantially higher monsoon rainfall during much of the

LIA (Sinha et al., submitted for publication). This observation is consistent with our suggestion of break-dominated conditions in the core monsoon areas during the LIA. On longer timescales, proxy records from the Indian sub-continent and the Arabian Sea indicate a contrasting north–south spatial pattern of monsoon precipitation during the early Holocene, which has been hypothesized to have resulted from persistence of the break-dominated monsoon regime at that time (Staubwasser, 2006; Staubwasser and Weiss, 2006).

4. Summary and implications

A high-resolution speleothem $\delta^{18}O$ record from Dandak Cave in central India documents a near millennial length history of monsoon rainfall and drought variability between AD 600–1500 (Sinha et al., 2007). Our reconstruction reveals a series of multiyear to multi-decade long droughts that occurred between the mid 14th and 15th centuries. Theoretical and observational constraints on the $\delta^{18}O$ of speleothem calcite during the instrumental period allow us to place the severity, frequency, and temporal durations of inferred droughts in the context of the 20th century monsoon droughts. Our analysis suggests that MMDs may have been marked by up to a 20–30% reduction in monsoon rainfall amounts (relative to the modern climatological mean) and at least one of the MMDs may have lasted as long as 30 years. While some droughts in India during the instrumental period were indeed marked by such drastic reductions in monsoon rainfall, their temporal duration pales in comparison to the megadroughts in our reconstruction. Within the margin of dating errors of individual proxy records, the MMDs in India appear to have occurred in temporal synchrony with MMDs reported in recent proxy reconstructions of from Vietnam (Buckley et al., 2010) and central China (Zhang et al., 2008) suggesting widespread spatial signatures of these droughts. The historical accounts and emerging archaeological data corroborate the occurrence of these megadroughts and a close temporal association of these droughts with widespread societal changes across the monsoon Asia implies that they were major causal forcing of these changes.

Emerging tree ring-based reconstructions of monsoon variability from SE Asia (Buckley et al., 2007; Sano et al., 2009) and India (Borgaonkar et al., 2010) suggest that the mid 14th–15th century megadroughts were the first in a series of spatially widespread megadroughts that occurred during the LIA. While the climate dynamics associated with the ENSO and its low frequency counterpart PDO, have been shown to exert considerable, albeit intermittent, influences on monsoon rainfall during the instrumental period, our analysis of proxy records do not reveal a clear role of the ENSO in causing these megadroughts. Nonetheless, it will be premature to discount the role of the tropical Pacific until additional unambiguous high-resolution ENSO sensitive proxy records become available.

Our study however, supports the suggestion that generally reduced monsoon in Asia were associated with cooler temperature in the extratropical latitudes in the Northern Hemisphere during the LIA. The drought-prone climate pattern was accentuated during several near-century length discrete cold events within the LIA, all of which occurred in temporal synchrony with globally (southward) shifted ITCZ and MMDs in the Indian monsoon domain. Utilizing modern observations that link weaker monsoon on land to enhanced convection in the (EEIO) (Krishnan et al., 2006), we propose that the causative forcings of the MMDs appear to be rooted in the seasonal dynamics of the ITCZ in the (EEIO), which are known to have been the cause of severe but short-lived droughts in India and SE Asia. We propose that episodic southward bias in the ITCZ (with respect to its mean location during the LIA) in the Indian Ocean may have produced a distinctly protracted "break-dominated" mode of circulation that promoted enhanced convection over the EEIO, which in turn, suppressed convection and rainfall over the continental monsoon regions. While today, the break phase of monsoon circulation causes widespread drought on intraseasonal timescale, a persistence of this mode of monsoon circulation on decadal timescale may have been instrumental in causing the MMDs.

The paleoclimate evidence presented in this paper raise an important question as to whether the sustained mode reversals in monsoon circulation could also occur in the future in response to either natural or anthropogenic forcing such as greenhouse and aerosol induced radiative changes. Our analysis of proxy records suggests that monsoon circulation and precipitation variability are both highly sensitive to temperature changes at extratropical latitudes through their impact on the mean position of the global ITCZ. This sensitivity is also evident during the instrumental period as illustrated by a coherent, albeit muted (with respect to the LIA) response of the global monsoon-ITCZ system to low amplitude multidecadal length (~60–80 years) fluctuations in the North Atlantic SSTs, which is commonly referred to as the Atlantic Multidecadal Oscillation (AMO) (Kerr, 2000). For example, the cooler phase of AMO has been associated with increased sea ice cover in the Arctic and glacial advances in the Swiss Alps (Denton and Broecker, 2008), increased precipitation in tropical S. America (Baines and Folland, 2007), and sustained episodes of weaker monsoon rainfall in India and SE Asia (Lu et al., 2006; Zhang and Delworth, 2006; Goswami et al., 2006b; Li et al., 2008). Instrumental records and proxy reconstructions of monsoon rainfall from several sites in monsoon Asia, including the Dandak Cave record, contain dominant spectral powers at periods that are similar to those with the observed AMO cycle (Berkelhammer et al., 2010). If the recurrent pattern of SST variability in the North Atlantic indeed exists and it is the result of internal dynamics operating on multidecadal timescales (Park and Latif, 2008) or through an external forcing mechanism (e.g., solar variability), then future modulations in the monsoon rainfall may be tied to the amplitude of SST changes in the North Atlantic region.

In addition to the monsoon's sensitivity to extratropical temperatures, the continental monsoon precipitation variability is intrinsically tied to the seasonal dynamics of convection in the Indian Ocean and its interaction with the monsoonal winds (e.g., Krishnan et al., 2006; Gadgil et al., 2007). Observational data indicate an increasing propensity of break monsoon spells over the Indian sub-continent in the recent decades due to rising SSTs and enhanced convection in the equatorial Indian Ocean (Ramesh Kumar et al., 2009). Increased occurrence of break spells, delayed onset, and weaker cross-equatorial monsoonal winds are robust features in simulations with a high-resolution nested climate model in response to projected greenhouse forcing in the 21st century (Ashfaq et al., 2009). Additionally, a weaker monsoon circulation during the 21st century is projected to arise from reduced upper-tropospheric thermal contrast between Asia and the IO, which results from enhanced upper-tropospheric warming over the tropical Indian Ocean due to increased latent heating. This response overrides the increasing surface land–sea thermal gradient and increasing water vapor holding capacity of the atmosphere-factors that would otherwise cause an increase in monsoon precipitation over the land (Sun et al., 2010). These studies raise an intriguing possibility that a substantial increase in the heat content of the EEIO in response to increasing greenhouse forcing may tip the monsoon into a sustained break mode leading to reoccurrence of protracted droughts in the future. If so, sustained mode reversals in the monsoon circulation and precipitation patterns are possible responses to both anomalously warm temperatures at tropical latitudes in the IO and cool temperatures at extratropical latitudes in the North Atlantic.

The tragic experience of the drought in 2002 in India suggests that the present-day water-resource infrastructure and planning are barely sufficient to meet the welfare of billions of people during a single season of anomalous weak monsoon, let alone a protracted failure. We remind the reader that a mere 10% reduction in seasonal rainfall in many regions of monsoon Asia is sufficient to trigger a major drought. A reoccurrence of a protracted interval of drought with seemingly modest departures of monsoon rainfall is bound to overwhelm the adaptive capabilities of societies in monsoon Asia unless a longer term and a fuller range of monsoon's variability, as documented in the recent proxy records, is urgently incorporated into drought management and mitigation planning.

Acknowledgements

We are grateful to R. Krishnan (Indian Institute of Tropical Meteorology) and K. Anchukaitis (Lamont Doherty Earth Observatory) for critical reviews of our manuscript that considerably help improve the clarity of this submission. We thank Peter Webster for his insightful comments on the manuscript, M-A. Sicre and G. Massé for providing the Icelandic Shelf SST and IP25 biomarker data, respectively. This work was supported by the National Science Foundation grants to AS (ATM: 0823554), LDS (0502615), RLE and HC (ATM: 0502535) and Gary Comer Science and Education Foundation Grants to RLE (CC8 and CP41).

Appendix. Supplementary material

Supplementary data related to this article can be found online at doi:10.1016/j.quascirev.2010.10.005.

References

Aldenderfer, M., Zhang, Y., 2004. The prehistory of the Tibetan plateau to the 7th C. AD: perspectives and research from China and the west since 1950. J. World Prehistory 18, 1–55.
Annamalai, H., Slingo, J.M., 2001. Active/break cycles: Diagnosis of the intraseasonal variability of the Asian summer monsoon. Clim. Dyn. 18, 85–102.
Anderson, D.M., Overpeck, J.T., Gupta, A.K., 2002. Increase in Asian southwest monsoon during the past four centuries. Science 297, 596–599.
Ashfaq, M., Shi, Y., Tung, W., Trapp, R.J., Gao, X., Pal, J.S., Diffenbaugh, N.S., 2009. Suppression of south Asian summer monsoon precipitation in the 21st century. Geophys. Res. Lett. 36, L01704.
Ashok, K., Guan, Z., Saji, N.H., Yamagata, T., 2004. Individual combined influences of the ENSO and Indian Ocean Dipole on the Indian summer monsoon. J. Clim. 17, 3141–3155.
Ashok, K., Behera, S.K., Rao, S.A., Weng, H., Yamagata, T., 2007. El Niño Modoki and its possible teleconnection. J. Geophys. Res. 112, C11007. doi:10.1029/2006JC003798.
Asmerom, Y., Polyak, V.P., Burns, S.J., 2010. Variable winter moisture in the southwestern United States linked to rapid glacial climate shifts. Nat. Geosci. 3, 114–117.
Baines, P.G., Folland, C.K., 2007. Evidence for a rapid global climate shift across the late 1960s. J. Clim. 20, 2721–2744.
Berkelhammer, M., Sinha, A., Mudelsee, M., Cannariato, K.G., 2010. Persistent multidecadal power in the Indian summer monsoon. Earth Planet. Sci. Lett. 290, 166–172.
Black, D.E., Abahazi, M.A., Thunell, R.C., Kaplan, A., Tappa, E.J., Peterson, L.C., 2007. An 8-century tropical Atlantic SST record from the Cariaco Basin: baseline variability, twentieth-century warming, and Atlantic hurricane frequency. Paleoceanography, 22–27.
Boos, W.R., Kuang, Z., 2010. Dominant control of the South Asian monsoon by orographic insulation versus plateau heating. Nature 463, 218–222.
Borgaonkar, H.P., Sikdera, A.B., Rama, S., Panta, G.B., 2010. El Niño and related monsoon drought signals in 523-year-long ring width records of teak (*Tectona grandis* L.F.) trees from south India. Palaeogeogr. Palaeoclimatol. Palaeoecol. 285, 74–84.
Bowen, G.J., Revenaugh, J., 2003. Interpolating the isotopic composition of modern meteoric precipitation. Water Resour. Res. 39 (10), 1299.
Broccoli, A.J., Dahl, K.A., Stouffer, R.F., 2006. Response of the ITCZ to northern hemisphere cooling. Geophys. Res. Lett. 33, GL024546.
Buckley, B.M., Anchukaitis, K.J., Penny, D., Fletcher, R., Cook, E.R., Sano, M., Nam, L.C., Wichienkeeo, A., Minh, T.T., Hong, T.M., 2010. Climate as a contributing factor in the demise of Angkor, Cambodia. Proc. Natl. Acad. Sci. U.S.A. 107, 6748–6752.
Buckley, B.M., Palakit, K., Duangsathaporn, K., Sanguantham, P., Prasomsin, P., 2007. Decadal scale droughts over northwestern Thailand over the past 448 years: links to the tropical Pacific and Indian Ocean sectors. Clim. Dyn. 29, 63–71.
Burns, S.J., Fleitmann, D., Matter, A., Kramers, J., Al-Subbary, A.A., 2003. Indian Ocean climate and an absolute chronology over Dansgaard/Oeschger events 9 to 13. Science 301, 1365–1367.
Cane, M., 2010. Climate: a moist model monsoon. Nature 463, 163–164.
Chao, W.C., 2000. Multiple quasi equilibria of the ITCZ and the origin of monsoon onset. J. Atmos. Sci. 57, 641–651.
Chao, W.C., Chen, B.D., 2001. The origin of monsoon. J. Atmos. Sci. 58, 3497–3507.
Cheng, H., Fleitmann, D., Edwards, R.L., Wang, X.F., Cruz, F.W., Auler, A.S., Mangini, A., Wang, Y.J., Burns, S.J., Matter, A., 2009. Timing and structure of the 8.2 ky event inferred from d18O records of stalagmites from China, Oman and Brazil. Geology 37, 1007–1010.
Cheng, H., Edwards, R.L., Wang, Y., Kong, X., Ming, Y., Kelly, M.J., Wang, X., Gallup, C.D., Liu, W., 2006. A penultimate glacial monsoon record from Hulu Cave and two-phase glacial terminations. Geology 34 (3), 217–220.
Chiang, J.C.H., Bitz, C.M., 2005. Influence of high latitude ice cover on the marine Intertropical Convergence Zone. Clim. Dyn. 25, 477–496.
Clement, A.C., Seager, R., Cane, M.A., Zebiak, S.E., 1996. An ocean dynamical thermostat. J. Clim. 9, 2190–2196.
Cobb, K., Charles, C.D., Cheng, H., Edwards, R.L., 2003. El Niño/Southern Oscillation and tropical Pacific climate during the last millennium. Nature 424, 271–276.
Conroy, J.L., Overpeck, J.T., Cole, J.E., Shanahan, T.M., Steinitz-Kanan, M., 2008. Holocene changes in eastern tropical Pacific climate inferred from a Galápagos lake sediment record. Quat. Sci. Rev. 27, 1166–1180.
Conroy, J.L., Restrepo, A., Overpeck, J.T., Steenitz-Kanan, M., Cole, J.E., Bush, M.B., Colinvaux, P.A., 2009. Unprecedented recent warming of surface temperatures in the eastern tropical Pacific Ocean. Nat. Geosci. 2, 46–50.
Conroy, J.L., Overpeck, J.T., Cole, J.E., 2010. El Niño/Southern Oscillation and changes in the zonal gradient of tropical Pacific sea surface temperature over the last 1.2 ka. PAGES News 18.
Cook, E.R., AnchukaitisBuckley, B.M., D'Arrigo, R.D., Jacoby, G.C., Wright, W.E., 2010. Asian monsoon failure and megadrought during the last millennium. Science 328, 486–489.
Cruz Jr., F.W., Burns, S.J., Karmann, I., Sharp, W.D., Vuille, M., Cardoso, A.O., Ferrari, A.J., Dias, P.L.S., Viana Jr., O., 2005. Insolation driven changes in atmospheric circulation over the past 116,000 years in subtropical Brazil. Nature 434, 63–66.
Dando, W.A., 1980. The Geography of Famine. John Wiley, New York, p. 209.
Delworth, T.L., Mann, M.E., 2000. Observed and simulated multidecadal variability in the Northern Hemisphere. Clim. Dyn. 16, 661–676.
Denton, G.H., Broecker, W.S., 2008. Wobbly ocean conveyor circulation during the Holocene? Quat. Sci. Rev. 27, 1939–1950.
Dre'ze, J., 1995. Famine prevention in India. In: Dre'ze, J., Sen, A., Hussain, A. (Eds.), The Political Economy of Hunger: Selected Essays. Clarendon Press, Oxford, pp. 69–178.
Dykoski, C.A., Edwards, R.L., Cheng, H., Yuan, D.X., Cai, Y.J., Zhang, M.L., Lin, Y.S., Qing, J.M., An, Z.S., Revenaugh, J., 2005. A high-resolution, absolute-dated Holocene and deglacial Asian monsoon record from Dongge Cave, China. Earth Planet. Sci. Lett. 233, 71–86.
Fairchild, I.J., Smith, C.L., Baker, A., Fuller, L., Spötl, C., Mattey, D., McDermott, F., 2006. Modification and preservation of environmental signals in speleothems. Earth-Sci. Rev. 75, 105–153.
Fan, F., Mann, M., Ammann, C., 2009. Understanding changes in the Asian Summer Monsoon over the past millennium: insights from a long-term coupled model simulation. J. Clim. 22, 1736–1748.
Feng, S., Hu, Q., 2008. How the North Atlantic multidecadal oscillation may have influenced the Indian summer monsoon during the past two millennia. Geophys. Res. Lett., L01707.
Fleitmann, D., Burns, S.J., Mangini, A., Mudelsee, M., Kramers, J., Villa, I., Neff, U., Subbary, A.-A., Buettner, A., Hippler, D., Matter, A., 2007. Holocene ITCZ and Indian monsoon dynamics recorded in stalagmites from Oman and Yemen (Socotra). Quat. Sci. Rev. 26, 170–188.
Fleitmann, D., Burns, S.J., Mudelsee, M., Neff, U., Kramers, J., Mangini, A., Matter, A., 2003. Holocene forcing of the Indian monsoon recorded in a stalagmite from Southern Oman. Science 300, 1737–1739.
Fleitmann, D., Burns, S.J., Neff, U., Mudelsee, M., Mangini, A., Matter, A., 2004. Palaeoclimatic interpretation of high-resolution oxygen isotope profiles derived from annually laminated speleothems from southern Oman. Quat. Sci. Rev. 23, 935–945.
Frankenberg, C., Yoshimura, K., Warneke, T., Aben, I., Butz, A., Deutscher, N., Griffith, D., Hase, F., Notholt, J., Schneider, M., Schrijver, H., Rockmann, T., 2009. Dynamic Processes governing lower-tropospheric HDO/H_2O ratios as observed from space and ground. Science 325, 1374–1377.
Gadgil, S., Gadgil, S., 2006. The Indian monsoon, GDP and agriculture. Econ. Polit. Weekly 41, 4887–4895.
Gadgil, S., 2003. The Indian monsoon and its variability. Annu. Rev. Earth Planet. Sci. 31, 429–467.
Gadgil, S., Rajeevan, M., Francis, P.A., 2007. Monsoon variability: links to major oscillations over the equatorial Pacific and Indian oceans. Curr. Sci. 93, 182–194.

Gadgil, S., Vinaychandran, P.N., Francis, P.A., Gadgil, S., 2004. Extremes of Indian summer monsoon rainfall, ENSO, equatorial Indian Ocean Oscillation. Geophys. Res. Lett. 31, L12213.
Gershunov, A., Barnett, T.P., 1998. Interdecadal modulation of ENSO teleconnections. Bull. Am. Meteorol. Soc. 79, 2715–2726.
Goswami, B.N., 2005. South asian monsoon (Chapter 2). In: Lau, William K.M., Waliser, Duane E. (Eds.), Intraseasonal Variability of the Atmosphere-Ocean Climate System. Praxis, Springer, Berlin Heidelberg, pp. 19–61.
Goswami, B.N., Wu, G., Yasunari, T., 2006a. The annual cycle, intraseasonal oscillations, and roadblock to seasonal predictability of the asian summer monsoon. J. Clim. 19, 5078–5098.
Goswami, B.N., Madhusoodanan, M.S., Neema, C.P., Sengupta, D., 2006b. A physical mechanism for the North Atlantic SST influence on the Indian summer monsoon. Geophys. Res. Lett. 33, L02706.
Grove, R., 1998. Global impact of the 1789–93 El Niño. Nature 393, 318–319.
Gupta, A.K., Anderson, D.M., Overpeck, J.T., 2003. Abrupt changes in the Asian southwest monsoon during the Holocene and their links to the North Atlantic Ocean. Nature 421, 354–357.
Haug, G.H., Hughen, K.A., Sigman, D.M., Peterson, L.C., Rohl, U., 2001. Southward migration of the intertropical convergence zone through the Holocene. Science 293, 1304–1308.
Hodell, D.A., Brenner, M., Curtis, J.H., 2005. Climate change on the Yucatan Peninsula during the Little ice age. Quat. Res. 63, 109–121.
Holzhauser, H., Magny, M., Zumbuhl, H.J., 2005. Glacier and lake-level variation in west-central Europe over the last 3500 years. The Holocene 15, 789–801.
Hoyos, C.D., Webster, P.J., 2007. The role of intraseasonal variability in the nature of Asian monsoon precipitation. J. Clim. 20, 4402–4424.
Hu, C., Henderson, G.M., Huang, J., Xie, S., Sun, Y., Johnson, K.R., 2008. Quantification of Holocene Asian monsoon rainfall from spatially separated cave records. Earth Planet. Sci. Lett. 266, 221–232.
Indrapala, K., 1971. The Collapse of the Rajarata Civilization and the Drift to the Southwest. University of Ceylon Press.
Joseph, S., Sahai, A.K., Goswami, B.N., 2009. Eastward propagating MJO during boreal summer and Indian monsoon droughts. Clim. Dyn. 32, 1139–1153.
Kaspari, S., Mayewski, P.A., Kang, S., Sneed, S., Kreutz, K., Introne, D., Hooke, R., Maasch, K., Qin, D., Ren, J., 2007. Reduction in northward incursions of the South Asian Monsoon since ˜1400 A.D. inferred from a Mt. Everest ice core. Geophys. Res. Lett. 34, L16701.
Kerr, R.A., 2000. A North Atlantic climate pacemaker for the centuries. Science 288, 1984–1986.
Knight, J.R., Allan, R.J., Folland, C.K., Vellinga, M., Mann, M.E., 2005. A signature of persistent natural thermohaline circulation cycles in observed climate. Geophys. Res. Lett. 32, L20708.
Krishnamurthy, V., Shukla, J., 2000. Intraseasonal and interannual variability of rainfall over India. J. Clim. 13, 4366–4377.
Krishnan, R., Kumar, V., Sugi, M., Yoshimura, J., 2009. Internal feedbacks from monsoon-midlatitude interactions during droughts in the Indian summer monsoon. J. Atmos. Sci. 66, 553–578.
Krishnan, R., Mujumdar, M., Vaidya, V., Ramesh, K.V., Satyan, V., 2003. The abnormal Indian summer monsoon of 2000. J. Clim. 16, 1177–1194.
Krishnan, R., Ramesh, K.V., Samala, B.K., Meyers, G., Slingo, J.M., Fennessy, M.J., 2006. Indian Ocean monsoon coupled interactions and impending monsoon droughts. Geophys. Res. Lett. 33, L08711.
Krishnan, R., Sugi, M., 2003. Pacific decadal oscillation and variability of the Indian summer monsoon rainfall. Clim. Dyn. 21, 233–242.
Krishnan, R., Zhang, C., Sugi, M., 2000. Dynamics of breaks in the Indian summer monsoon. J. Atmos. Sci. 57, 1354–1372.
Kug, J.-S., Jin, F.-F., An, S.I., 2009. Two types of El Niño events: cold tongue El Niño and warm pool El Niño. J. Clim. 22, 1499–1515.
Kumar, K.K., Rajagopalan, B., Hoerling, M., Bates, G., Cane, M., 2006. Unraveling the mystery of Indian monsoon failure during El Niño. Science 314, 115–119.
Kumar, K.K., Rajagopalan, B., Cane, M., 1999. On the weakening relationship between the Indian monsoon and ENSO. Science 25, 2156–2159.
Kumar, R.R., Kumar, K.K., Ashrit, R.G., Patwardhan, S.K., Pant, G.B., 2002. In: Shukla, J., et al. (Eds.), Climate Change in India. Tata McGraw Hill, New Delhi, India, pp. 24–75.
Lawrence, D.M., Webster, P.J., 2001. Interannual variations of the intraseasonal oscillations in the South Asian Summer monsoon. J. Clim. 14, 2910–2922.
Lawrence, D.M., Webster, P.J., 2002. The boreal summer intraseasonal oscillations: relationship between northward and eastward movement of convection. J. Atmos. Sci. 59, 1593–1606.
Leiberman, V., 2003. Strange Parallels: Southeast Asia in Global Context C. 800–1830. In: Integration on the Mainland, vol. 1. CambridgeUniversity Press, 484 pp.
Li, S., Perlwitz, J., Quan, X., Hoerling, M.P., 2008. Modelling the influence of North Atlantic multidecadal warmth on the Indian summer rainfall. Geophys. Res. Lett. 35, L05804.
Lu, R., Dong, B., Ding, H., 2006. Impact of the Atlantic multidecadal oscillation on the asian summer monsoon. Geophys. Res. Lett. 33, L24701.
Lund, D.C., Lynch-Stieglitz, J., Curry, W.B., 2006. Gulf Stream density structure and transport during the past millennium. Nature 444, 601–604.
MacDonald, G.M., Case, R.A., 2005. Variations in the Pacific decadal oscillation over the past millennium. Geophys. Res. Lett. 32, L08703.
Maharatna, A., 1996. The Demography of Famines: An Indian Historical Perspective. OxfordUniv. Press, Delhi, India, p. 317.
Mann, M.E., Cane, M.A., Zebiak, S.E., Clement, A., 2005. Volcanic and solar forcing of the tropical Pacific over the past 1000 years. J. Clim. 18, 447–456.
Mann, M.E., Zhang, Z., Rutherford, S., Bradley, R., Hughes, M., Shindell, D., Ammann, C., Faluvegi, G., Ni, F., 2009. Global signatures and dynamical origins of the little ice age and medieval climate anomaly. Science 326, 1256–1260.
Massé, G., Rowland, S.J., Sicre, M.-A., Jacob, J., Jansen, E., Belt, S.T., 2008. Abrupt climate changes for Iceland during the last millennium: evidence from high resolution sea ice reconstructions. Earth Planet. Sci. Lett. 269, 564–568.
Meehl, G.A., Hu, A., 2006. Megadroughts in the Indian monsoon region and southwest North America and a mechanism for associated multidecadal Pacific sea surface temperature anomalies. J. Clim. 19, 1605–1623.
Meehl, G.A., Arblaster, J.M., Collins, W.D., 2008. Effects of black carbon aerosols on the Indian monsoon. J. Clim. 21, 2869–2882.
Moy, C.M., Seltzer, G.O., Rodbell, D.T., Anderson, D.M., 2002. Variability of El Niño southern oscillation activity at millennial timescales during the Holocene epoch. Nature 420, 162–165.
Newton, A., Thunell, R., Stott, L.D., 2006. Climate and hydrographic variability in the Indo-Pacific Warm Pool during the last millennium. Geophys. Res. Lett. 33, L19710.
Nicholson, S., 2000. The nature of rainfall variability over Africa on time scales of decades to millennia. Glob. Planet Change 26, 137–158.
Nicholson, S., Entekhabi, D., 1987. Rainfall variability in equatorial and Southern Africa: relationships with sea-surface temperature atmosphere coupling. J. Appl. Meteorol. Clim. 26, 561–578.
Nicholson, S., Kim, J., 1997. The relationship of the El Niño-southern oscillation to African rainfall. Int. J. Climatol. 17, 117–135.
Nigam, S., 1994. On the dynamical basis for the Asian summer monsoon rainfall–El Niño relationship. J.Clim. 7, 1750–1770.
Ogilvie, A.E.J., 1984. The past climate and sea-ice record from Iceland. Part 1: data to A.D. 1780. Clim. Change 6, 131–152.
Ogilvie, A.E.J., 1991. Climatic changes in Iceland ca. 865 to 1595. Acta Archaeologica 61, 233–251.
Oppo, D., Rosenthal, Y., Linsley, B.K., 2009. 2,000-year-long temperature and hydrology 2,000-year-long temperature and hydrology reconstructions from the Indo-, temperature and hydrology reconstructions from the Indo-Pacific warm pool. Nature 460, 1113–1116.
Overpeck, J., Anderson, D., Trumbore, S., Prell, W., 1996. The southwest Indian Monsoon over the last 18000 years. Clim. Dyn. 12, 213–225.
Pant, G.B., Rupa-Kumar, K.N., Sontakke, A., Borgaonkar, H.P., 1993. Climate variability over India on century and longer time scales. In: Keshavamurty, R.N., Joshi, P.C. (Eds.), Tropical Meteorology. Tata McGraw-Hill, New Delhi, India, pp. 149–158.
Park, W., Latif, M., 2008. Multidecadal and multicentennial variability of the meridional overturning circulation. Geophys. Res. Lett. 35, L22703.
Parthasarathy, B., Munot, A.A., Kothawale, D.R., 1995. Monthly and Seasonal Rainfall Series for All India, Homogeneous Regions and Meteorological Subdivisions: 1871–1994, Res. Rep. RR-065, 113 pp.. Indian Inst. of Trop. Meteorol., Pune, India.
Petech, L., 1997. Western Tibet: historical introduction. In: Klimburg- Salter, D. (Ed.), Tabo: a Lamp for the Kingdom. Thames and Hudson, London, pp. 229–256.
Poore, R.Z., Quinn, T.M., Verardo, S., 2004. Century-scale movement of the Atlantic Intertropical Convergence Zone linked to solar variability. Geophys. Res. Lett. 31, L12214.
Power, S., Casey, T., Folland, C., Colman, A., Mehta, V., 1999. Inter-decadal modulation of the impact of ENSO on Australia. Clim. Dyn. 15, 319–324.
Rajeevan, M., Gadgil, S., Bhate, J., 2010. Active and break spells of the Indian summer monsoon. J. Earth Syst. Sci. 119, 229–247.
Ramamurthy, K., 1969. Monsoon of India: Some Aspects of the 'Break' in the Indian Southwest Monsoon during July and August. Forecasting Manual 1–57 No. IV 18.3. India Met. Dept., Poona, India.
Ramesh Kumar, M.R., Krishnan, R., Sankar, S., Unnikrishnan, A.S., Pai, D.S., 2009. Increasing 'Break-Monsoon' conditions over India — Role of ocean–atmosphere processes in the Indian ocean. Geosci. Rem. Sens. Lett. IEEE 6 (2), 332–336.
Rasmussen, E.M., Carpenter, T.H., 1982. Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño. Mon. Weather Rev. 110, 354–384.
Rein, B., Luckge, A., Sirocko, F., 2004. A major Holocene ENSO anomaly during the medieval period. Geophys. Res. Lett. 31, L17211.
Reuter, J., Stott, L., Khider, D., Sinha, A., Cheng, H., Edwards, R.L., 2009. A new perspective on the hydroclimate variability in northern South America during the Little Ice Age. Geophys. Res. Lett. 36, L21706.
Richey, J.N., Poore, R.Z., Flower, B.P., Quinn, T.M., 2007. A 1400-year multiproxy record of climate variability from the northern Gulf of Mexico. Geology 35 (5), 423–426.
Rodell, M., Velicogna, I., Famiglietti, J.S., 2009. Satellite-based estimates of groundwater depletion in India. Nature 460, 999–1002.
Sachs, J.P., Sachse, D., Smittenberg, R.H., Zhang, Z., Battisti, D.S., Golubic, S., 2009. Southward movement of the Pacific Intertropical 247 convergence zone AD 1400–1850. Nat. Geosci. 2, 519–525.
Salinger, M.J., Renwick, J.A., Mullan, A.B., 2001. Interdecadal Pacific oscillation and south Pacific climate. Int. J. Climatol. 21, 1705–1721.
Sano, M., Buckley, B.M., Sweda, T., 2009. Tree-ring based hydroclimate reconstruction over northern Vietnam from Fokienia hodginsii: eighteenth century mega-drought and tropical Pacific influence. Clim. Dyn. 33, 331–340.

Schulz, H., von Rad, U., Erienkeuser, H., 1998. Correlation between Arabian Sea and Greenland climate oscillations of the past 110,000 years. Nature 393, 54–57.

Shukla, J., 1987. Interannual variability of monsoons. In: Fein, J.S., Stephens, P.L. (Eds.), Monsoons. Wiley and Sons, New York, pp. 399–464.

Sicre, M.-A., Jacob, J., Ezat, U., Rousse, S., Kissel, C., Yiou, P., Eiríksson, J., Knudsen, K.L., Jansen, E., Turon, J.-L., 2008. Decadal variability of sea-surface temperatures off North Iceland over the last 2000 years. Earth Planet. Sci. Lett. 268, 137–142.

Sikka, D.R., Gadgil, S., 1980. On the maximum cloud zone and the ITCZ over India longitude during the Southwest monsoon. Mon. Weather Rev. 108, 1840–1853.

Sikka, D.R., 1980. Some aspects of the large scale fluctuations of summer monsoon rainfall over India in relation to fluctuations in the planetary and regional scale circulation parameters. Proc. Indian Acad. Sci. Earth Planet. Sci. 89, 179–195.

Sikka, D.R., 1999. Monsoon Droughts in India. Joint COLA/CARE. Tech Report # 2.

Sikka, D.R., 2003. Evaluation of monitoring and forecasting of summer monsoon over India and a review of monsoon drought of 2002. Proc. Indian Natl. Acad. Sci. 69, 479–504.

Sinha, A., Cannariato, K.G., Stott, L.D., Cheng, H., Edwards, R.L., Yadava, M.G., Ramesh, R., Singh, I.B., 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.

Sinha, A., Cannariato, K.G., Stott, L.D., Li, H.-C., You, C.-F., Cheng, H., Edwards, R.L., Singh, I.B., 2005. Variability of southwest Indian summer monsoon precipitation during the Bølling–Allerød. Geology 33, 813–816.

Sinha, A., Berkelhammer, M., Stott, L.D., Mudelsee, M., Cheng, H., Biswas, J. 'Internal' forcing of Indian summer monsoon precipitation during the last millennium. Science, submitted for publication.

Srinivasan, J., Joshi, P.C., 2007. What have learned about the Indian monsoon from satellite data. Curr. Sci. 93, 165–172.

Staubwasser, M., 2006. An overview of Holocene South Asian monsoon records—monsoon domains and regional contrasts. J. Geol. Soc. India 68, 433–446.

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

Sun, Y., Ding, Y., Dai, A., 2010. Changing links between South Asian summer monsoon circulation and tropospheric land sea thermal contrasts under a warming scenario. Geophys. Res. Lett. 37, L02704.

Thera, R.P., 1967. Jinakalamali Prakorn Translated into Thai by Saeng Monwitoon. Mitra Nara Publishing, Bangkok, Thailand [in Thai].

Tierney, J.E., Oppo, D.W., Rosenthal, Y., Russell, J.M., Linsley, B.K., 2009. Coordinated hydrological regimes in theIndo-Pacific region during the past two millennia. Paleoceanography 25, PA1102.

Timmermann, A., Okumura, Y., An, S.I., Clement, A., Dong, B., Guilyardi, E., Hu, A., Jungclaus, J.H., Renold, M., Stocker, T.F., Stouffer, R.J., Sutton, R., Xie, S.P., Yin, J., 2007. The Influence of a weakening of the Atlantic meridional overturning circulation on ENSO. J. Clim. 20, 4899–4919.

Trenberth, K.E., Stepaniak, D.P., Caron, J.M., 2000. The global monsoon as seen through the divergent atmospheric circulation. J. Clim. 13, 3969–3993.

Tomas, R., Webster, P.J., 1997. The role of inertial instability in determining the location and strength of near-equatorial convection. Q. J. Roy. Meterol. Soc. 123, 1445–1482.

Tomas, R., Holton, J.R., Webster, P.J., 1999. The influence of cross-equatorial pressure gradients on the location of near-equatorial convection. Q. J. Roy. Meterol. Soc. 125, 1107–1127.

Uemura, R., Matsui, Y., Yoshimura, K., Motoyama, H., Yoshida, N., 2008. Evidence of deuterium excess in water vapor as an indicator of ocean surface conditions. J. Geophys. Res. Atmos. 113, D19114.

Vellinga, M., Wood, R.A., 2002. Global climatic impacts of a collapse of the Atlantic thermohaline circulation. Clim. Change 54, 251–267.

Verschuren, D., Laird, K.R., Cumming, B.F., 2000. Rainfall and drought in equatorial East Africa during the past 1,100 years. Nature 403, 410–414.

Vitali, R. 1996. The Kingdoms of Guge Purhrang. Tho-lin dpal dpe med lhun gyis grub pa'i gtsug lag khan lo 1000 'khor ba'i rjes dran mdzad sgo'i go sgrig tshogs chun gis dpar skrun zus. Dharamasala, India.

Vuille, M., Werner, M., Bradley, R.S., Keimig, F., 2005. Stable isotopes in precipitation in the Asian monsoon region. J. Geophys. Res. 110, D23108.

Wang, P., 2009. Global monsoon in a geological perspective. Chin. Sci. Bull. 54, 1113–1136.

Wang, X.F., Auler, A.S., Edwards, R.L., Cheng, H., Cristalli, P.S., Smart, P.L., Richards, D.A., Shen, C.-C., 2004. Wet periods in northeastern Brazil over the past 210 kyr linked to distant climate anomalies. Nature 432, 740–743.

Wang, X.F., Auler, A.S., Edwards, R.L., Cheng, H., Ito, E., Solheid, M., 2006. Interhemispheric anti-phasing of rainfall during the last glacial period. Quat. Sci. Rev. 25, 3391–3403.

Wang, Y., Cheng, H., Edwards, R.L., Kong, X., Shao, X., Chen, S., Wu, J., Jiang, X., Wang, X., An, Z., 2008. Millennial- and orbital-scale changes in the East Asian monsoon over the past 224,000 years. Nature 10, 1038.

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

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

Weldeab, S., Lea, D.W., Schneider, R.R., Anderson, N., 2007. 155,000 years of West African monsoon and ocean thermal evolution. Science 316, 1303–1307.

Webster, P.J., Magana, V.O., Palmer, T.N., Shukla, J., Tomas, R.T., Yanai, M., Yasunari, T., 1998. Monsoons: processes, predictability and the prospects of prediction. J. Geophys. Res. 103 (C7), 14451–14510.

Yadava, M.G., 2002. Stable isotope systematics in cave calcites: implications to past climatic changes in tropical India. Ph.D. thesis, Phys. Res. Lab., Navrangpura, India, 207 pp.

Yeh, S.W., Kug, J.S., Dewitte, B., Kwon, M.H., Kirtman, B.P., Jin, F.F., 2009. El Niño in a changing climate. Nature 461, 511–514.

Yoshimura, K., Kanamitsu, M., Noone, D., Oki, T., 2008. Historical isotope simulation using Reanalysis atmospheric data. J. Geophys. Res. Atmos. 113, D19108.

Yuan, D., Cheng, H., Edwards, R.L., Dykoski, C.A., Kelly, M.J., Zhang, M., Qing, J., Lin, Y., Wang, Y., Wu, J., Dorale, J.A., An, Z., Cai, Y., 2004. Timing, duration, and transitions of the Last Interglacial Asian monsoon. Science 304, 575–578.

Zebiak, S.E., Cane, M.A., 1987. A model El Nino-southern oscillation. Mon. Weather Rev. 115, 2262–2278.

Zhang, P.Z., Cheng, H., Edwards, R.L., Chen, F.H., Wang, Y.J., Yang, X.L., Liu, J., Tan, M., Wang, X.F., Liu, J.H., An, C.L., Dai, Z.B., Zhou, J., Zhang, D.Z., Jia, J.H., Jin, L.Y., Johnson, K.R., 2008. A test of climate, sun, and culture relationships from an 1810-year Chinese cave record. Science 322, 940–942.

Zhang, R., Delworth, T.L., 2005. Simulated tropical response to a substantial weakening of the Atlantic thermohaline circulation. J. Clim. 18, 1853–1860.

Zhang, R., Delworth, T.L., 2006. Impact of Atlantic multidecadal oscillations on India/Sahel rainfall and Atlantic hurricanes. Geophys. Res. Lett. 33, L17712.