Earth and Planetary Science Letters 290 (2010) 166–172 No. 1-2

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

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

Persistent multidecadal power of the Indian Summer Monsoon

Max Berkelhammer [a,*], Ashish Sinha [b], Manfred Mudelsee [c,d], Hai Cheng [e], R. Lawrence Edwards [e], Kevin Cannariato [a]

[a] Department of Earth Sciences, University of Southern California, United States
[b] California State University, Dominguez Hills, United States
[c] Climate Risk Analysis, Hanover, Germany
[d] Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany
[e] Department of Geology and Geophysics, University of Minnesota, Minneapolis, United States

ARTICLE INFO

Article history:
Received 10 September 2009
Received in revised form 3 December 2009
Accepted 6 December 2009
Available online 4 January 2010

Editor: P. DeMenocal

Keywords:
paleoclimate
monsoon
isotope geochemistry
Atlantic Multidecadal Variability

ABSTRACT

The instrumental record of Indian Summer Monsoon (ISM) precipitation displays two complete manifestations of an inferred multidecadal cycle. Hitherto, no precipitation-sensitive proxy record from the Indian subcontinent has had the necessary resolution and length to adequately assess whether this observed feature is an inherent aspect of the ISM system on longer timescales. Here we present compelling evidence for persistence of this cycle using a millennial length (AD 600–1550) and sub-annually resolved speleothem oxygen isotope record ($\delta^{18}O$) from Dandak Cave in east-central India. The record displays a high degree of correlation with a speleothem-based Asian monsoon reconstruction from Wanxiang Cave in north-central China on annual to decadal timescales showing the regional significance of these findings. The observed period in our monsoon reconstruction is similar to that associated with the Gleissberg solar cycle and multidecadal sea surface temperature variability in the north Atlantic (AMO), both of which are often cited as the prominent pacemakers of ISM variability on multidecadal timescales. We document transient coherence between ISM precipitation amount and solar variability that persists exclusively in the century prior to and during the Medieval Climate Anomaly (nominally, AD 950–1300). The non-stationary nature of the SFV–monsoon relationship presented here may be evidence of the time-varying influence of tropical ocean–atmosphere dynamics on the solar–monsoon link; however, it is not possible to show with significance that this period of coherence is anything more than an artifact of two timeseries with similar spectra. We therefore, are inclined to interpret our record as evidence of a minimal role of solar variability in driving persistent multidecadal variability of the ISM. Multidecadal SST variability in the North Atlantic remains as the likely alternative driver for persistence of this cycle. Regardless of the causative mechanism(s), the amplitude and regional signature of the observed cycle in ISM precipitation highlight its societal importance with respect to forecasting ISM precipitation on multidecadal timescales.

1. Introduction

The Indian Summer Monsoon circulation is among the most profound features of the Earth's climate system (Webster, 1987). Seasonal (JJAS) precipitation associated with the ISM provides nearly 80% of the annual precipitation over the Indian subcontinent and is vital to sustaining the region's agriculture and rapidly growing economy (Gadgil et al., 2005). The instrument record of ISM precipitation (ca AD 1870) reveals prominent inter-annual to multidecadal precipitation variability, which has generated noted social and economic hardship (Gadgil et al., 2005). Historical documentary accounts (Maharatna, 1996) and a limited number of high-resolution proxy based reconstructions from the Indian subcontinent suggest that larger precipitation anomalies in the ISM have occurred on inter-annual to centennial timescales over the past 1–2 millennia (Staubwasser and Weiss, 2006; Sinha et al., 2007; Davis et al., 2005). These reconstructions underscore the need to understand the full spectrum of monsoon behavior on all timescales to improve predictive skill. Although there has been important progress with regard to forecasting on seasonal to inter-annual timescales (Luo et al., 2008), predicting ISM behavior at multidecadal time scales, particularly amidst increasing radiative forcing from rising greenhouse gas concentrations, remains a complex challenge.

The instrument record of ISM precipitation is characterized by a prominent 60–70-year cycle (Zhang and Delworth, 2006; Goswami et al., 2006). Area-weighted monsoon rainfall over India (AIR) was greater than the long-term mean between AD 1870 and 1900 and from AD 1930 to 1960. Conversely, the intervals between AD 1900 and

* Corresponding author.
E-mail address: berkelha@usc.edu (M. Berkelhammer).

0012-821X/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2009.12.017

1930 and AD 1960 to 1990s were characterized by lower than average rainfall (Gadgil et al., 2007). The principal goal of this study is to further characterize whether the multidecadal variability is persistently periodic and inherent to the ISM system or a transient aspect unique to the 20th century. If indeed these multidecadal features are a persistent feature of the ISM, a dynamical understanding of their origin would form the basis for reliable monsoon forecasting on timescales relevant to policy-makers (Goswami and Xavier, 2005).

External forcing from solar flux variability (SFV) has previously been implicated as a potential driver for low frequency variability of the ISM (Neff et al., 2001; Burns et al., 2002; Fleitmann et al., 2003; Agnihotri et al., 2002a). Work by Kodera (2004) has shown that the SFV–ISM relationship can persist at higher frequencies through direct invigoration of convection over the tropical Indian Ocean. Kodera (2004) shows that the solar influence on the monsoon arises as a consequence of the high concentrations of UV-sensitive ozone in the stratosphere, which allows even modest changes in solar flux to influence the vertical temperature gradient in the tropics, leading to more rigorous convection and thus increased summer rainfall over India. Both Kodera (2004) and Bhattacharyya and Narasimha (2005) provide evidence of a solar signature during the instrumental precipitation record from the Indian subcontinent. Haigh (1996) and Emile-Geay et al. (2007) present alternative mechanisms to modulate a solar signature on ISM through changes in Hadley circulation or by way of the solar influence on ENSO. Recent work by Meehl et al. (2009) shows that in order to generate the full magnitude of the observed solar signature on the climate system both the top-down stratospheric mechanism of Kodera (2004) and the bottom-up ocean–atmosphere mechanism of Haigh (1996) are necessary.

A number of studies also point to the influence of North Atlantic SST anomalies on ISM precipitation on inter-annual (Rajeevan and Sridhar, 2008), multidecadal (Zhang and Delworth, 2006; Goswami et al., 2006; Li et al., 2008), and millennial (Fleitmann et al., 2003; Gupta et al., 2003) timescales. Goswami et al. (2006) and Li et al. (2008) have shown that the warm (cold) phase of AMO is linked to increased (reduced) precipitation over the Indian subcontinent. The link between the North Atlantic and the ISM is achieved through changes in the meridional temperature gradient across the Indian subcontinent, a displacement of the ITCZ and through intensification of the low-level monsoon jet (Goswami et al., 2006; Li et al., 2008).

ENSO events also have a significant impact on ISM circulation on inter-annual timescales and lower frequency changes in the ENSO region during the 20th century appear also to bear a signature on multidecadal ISM variability (Goswami and Xavier, 2005; Wang and An, 2002; Ashok et al., 2004). However, the ENSO influence on ISM variability is non-stationary (Kumar et al., 2006) because of a dependency on the prevailing regional boundary conditions. For example, co-occurrence of warm (cold) ENSO and positive (negative) Indian Ocean Dipole (IOD) state can lead to cancellation of ENSO's impact on ISM (Ashok et al., 2004).

High-resolution ISM reconstructions are vital to assess pre-instrumental patterns of ISM variability and examine relationships with other components of the climate system. Speleothem-based reconstructions of ISM provide a direct terrestrial record of precipitation, however they currently only exist from regions where ISM has a peripheral influence (Neff et al., 2001; Burns et al., 2002; Fleitmann et al., 2003). Attempts to reconstruct ISM variability from within the core monsoon zone have relied on lacustrine sediments and lake level studies from NW India (Bryson and Swain, 1981; Enzel et al., 1999; Sharma et al., 2004; Prasad et al., 1997) and pollen and tree-ring sequences from the western Himalayas (Kar et al., 2002; Phadtare and Pant, 20006; Yadav and Singh, 2002). The former reconstructions generally suffer from chronologic uncertainties and coarse resolution while the latter are too short for the purposes of assessing persistent low frequency features. A number of studies have attempted to reconstruct ISM variability by utilizing marine proxies that reflect the extent of upwelling, wind intensity, and river discharge in Arabian Sea sediments (Gupta et al., 2003; von Rad et al., 1999; Agnihotri et al., 2002b; Anderson et al., 2002; Sarkar et al., 2000). These ISM reconstructions, however, have one key disadvantage in that they do not directly reflect precipitation changes, which is integral for assessing actual monsoon rainfall variability over continental India where prediction skill is most vital.

The goal of this study is to investigate whether there is a persistent multidecadal periodic component to ISM variability and quantify the timing of the maxima/minima, which is a task that has not been feasible with previous proxy records from the region. We used an annually resolved and absolute-dated speleothem oxygen isotope ($\delta^{18}O$) record from Dandak Cave from the core monsoon zone of India to investigate the power, persistence and cause(s) of multidecadal variability in the ISM. We validate the regional coherence and age controls of our reconstruction with a high-resolution record from China. A modified approach towards analysis of the spectra of paleoclimate timeseries is presented, which accounts for the fact that our data is both unevenly spaced and has age uncertainties that vary throughout the record. The result is a robust estimate of the power of the multidecadal cyclicity in the record. The cause of the observed periodic variability is tested against the commonly cited mechanisms for ISM variability.

2. Location and methodology

Dandak Cave is located at 19 °N and 82 °E at 400 m elevation (Fig. 1) within the zone referred to as Central India (CI) by Hoyos and Webster (2007). The instrumental rainfall record from CI correlates strongly with the AIR ($r^2 = 0.60$) and Southwest India ($r^2 = 0.59$) (Hoyos and Webster, 2007). Nearly a century long rainfall data from the nearest meteorological station (Jagdalpur) exhibits a classic unimodal rainfall distribution where over 80% of the annual precipitation falls during the summer monsoon season (Sinha et al., 2007). Work by Ashok et al. (2004) indicates this region has a significant (>95% confidence) anti-correlation with ENSO and a positive correlation with the strength of the IOD.

Instrumental data from the Global Network of Isotopes in Precipitation database and regional studies indicate that the amount effect is the leading cause of oxygen isotopic variability in monsoon season precipitation in this region (Bhattacharya et al., 2003; Yadava et al., 2004). Vuille et al. (2005) used the ECHAM-4 AGCM model fitted with isotope tracers to explore the amount effect across the Asian monsoon region and confirm that there is a negative correlation between $\delta^{18}O$ of precipitation and monsoon circulation from the Bay of Bengal across the central Indian subcontinent. They argue that in Central India stronger monsoon (sea to land) circulation generates increased convection, and subsequently an observable amount effect. On the basis of these studies we interpret $\delta^{18}O$ changes in Dandak Cave stalagmite (DAN-D) to primarily reflect variations in monsoon season rainfall amounts.

Initial $\delta^{18}O$ results from DAN-D stalagmite were published by Sinha et al. (2007).The $\delta^{18}O$ record presented here extends high-resolution analysis through the entire MCA capturing the transition into and out of this period. Our $\delta^{18}O$ timeseries now contains 1874 isotopic measurements (684 of which were presented in the original publication) spanning ~272 mm of speleothem calcite. The entire dataset including $\delta^{13}C$ measurements, which were made simultaneously with the $\delta^{18}O$ analyses, are included in Supplementary Tables 1 and 2. We have chosen not to include the $\delta^{13}C$ measurements in our discussion because of a lack of information that can be used to calibrate the variability.

The age model of DAN-D stalagmite presented in Sinha et al. (2007) is modified here using a Monte Carlo approach to generate a continuous representation of age uncertainty throughout the record and minimize the age uncertainty in certain intervals where

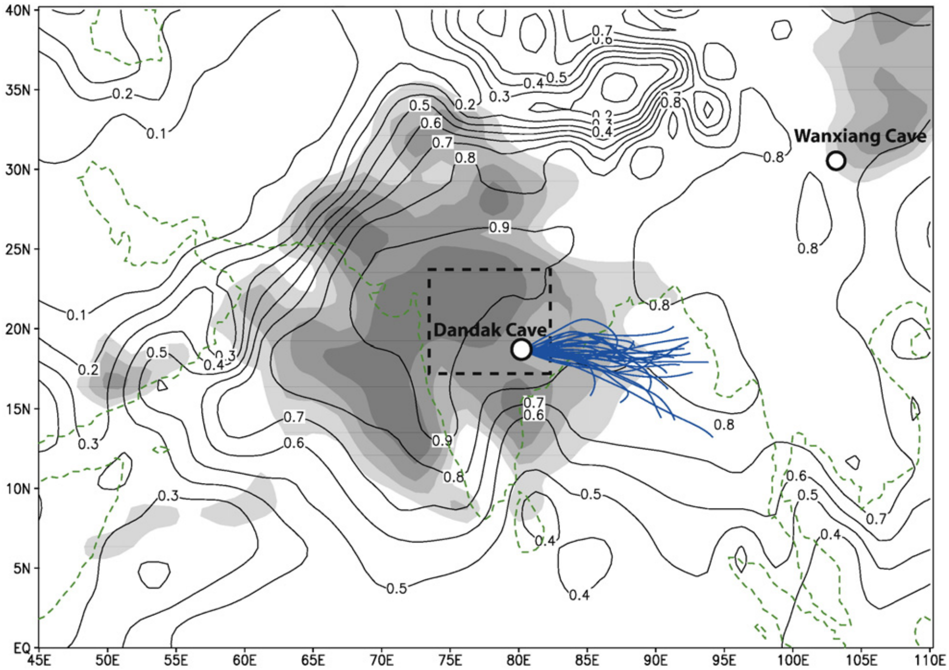

Fig. 1. Map showing location of Dandak and Wanxiang caves. Contour lines are used to show the fraction of annual rainfall that arrives during the summer monsoon season (July–Sept). Rainfall data is monthly averages from 1979–2007 using the CMAP database. The overlain shading denotes regions whose annual summer rainfall amount has a significant positive correlation with Central India monsoon rainfall from 1950–2008. The dark gray patch in the middle of India delineates the region that has a correlation coefficient of 0.8 with each subsequent lighter shade representing a 0.1 decrease in the *r*-value. Three-day back trajectories for air parcels during selected rainfall events affecting the Dandak site during the monsoon seasons of 2005–2007 done using the Air Resources Lab *Hysplit* Program are shown to loosely represent moisture source for the region (Draxler and Rolph, 2003).The dotted rectangle shows the approximate location of Central India as defined by Hoyos and Webster (2007).

the measured date is less precise. In this method, it is assumed that the actual age for a datum is distributed normally around the measured U/Th date (Supplementary Table 3). We simulate 1000 possible age models, by randomly distributing the dates around the reported age, based on the individual uncertainty estimates for each measurement (analytically-derived) and assume a linear interpolation between dates. In some instances the 2σ uncertainty in one date overlaps with the date of an adjacent sample, which periodically results in a spurious age model reversal. In order to minimize this, we modified our age model simulation so that in instances where adjacent samples have overlapping uncertainty within 2σ, maxima and minima ages are assigned that are scaled according to the reported analytical uncertainty. With this approach we are able to generate 90% confidence bands for the abscissa of our timeseries (Fig. 2). The age uncertainty of individual isotopic measurements is on average 12 yrs with some periods having uncertainties of less than 5 yrs.

To identify periodic components, the spectrum in the speleothem oxygen isotope records is calculated. We used the Lomb–Scargle periodogram in combination with Welch's Overlapped Sequence Averaging procedure (software: Redfit (Schulz and Mudelsee, 2002)) to analyze the unevenly spaced data directly, without interpolation and its distorting effect. A Welch window with three overlapping (50%) segments was selected to optimize bias/variance properties. Using a rectangular window with three segments gave similar results, attesting to the robustness of the result. We tested the null hypothesis "red-noise background with no significant periodic components" by means of Monte Carlo realizations (number of realizations, 2000) of a first-order autoregressive process for unevenly spaced timeseries (Schulz and Mudelsee, 2002). The Monte Carlo age model approach allows us to repeat the spectral analysis under the same setting (window type and number of segments) on 50 random iterations of our age model to test how minor adjustments to the age model affect the spectral properties of our record, following a similar method as Mudelsee et al. (2009). Any power with a period of greater than 125 yrs was excluded from consideration because our record is of insufficient length to capture signals of such a low frequency. Lastly, we use a band-pass filter for unevenly spaced timeseries (Schulz and Stattegger, 1997) on 50 randomly selected iterations of our age model to isolate variability in the range in which significant power was found (80–100 yrs).

3. Results and discussion

We have previously shown that variations in Dandak Cave $\delta^{18}O$ stalagmite record reflect broad-scale changes in ISM precipitation variability over Central India (Sinha et al., 2007). The $\delta^{18}O$ record presented in Fig. 3 contains several decadal to multidecadal intervals of weaker monsoon, which are corroborated by historical accounts of major drought-related famines in India between 7th and 16th centuries AD (Sinha et al., 2007). This aspect of our record reflects both its robust chronology and justification of using it as an accurate proxy for monsoon precipitation variations over continental India. To further evaluate broader regional relevance of our record, we compare Dandak $\delta^{18}O$ record with a recently published stalagmite $\delta^{18}O$ record from the Wanxiang cave in north-central China (Zhang et al., 2008). The Wanxiang cave $\delta^{18}O$ record has both excellent age constraints (<5 yrs) and is well-calibrated with instrumental data from this region (Zhang et al., 2008). The comparison between $\delta^{18}O$ records from Dandak and Wanxiang caves during the overlapping period (AD 600–1600) is presented in Fig. 3 on independent timescales, without any tuning or adjustments. The similarity between the two records is striking, highlighted by three contemporaneous maxima occurring near AD 900, AD 1050 and AD 1375. We calculate the correlation coefficients of sliding 50 yr windows between the two records to identify the extent to which the relationship evolves and find that while the average correlation is 0.27 ($p<0.01$), between AD 800 and AD 1420 the correlation coefficient of certain windows reaches values

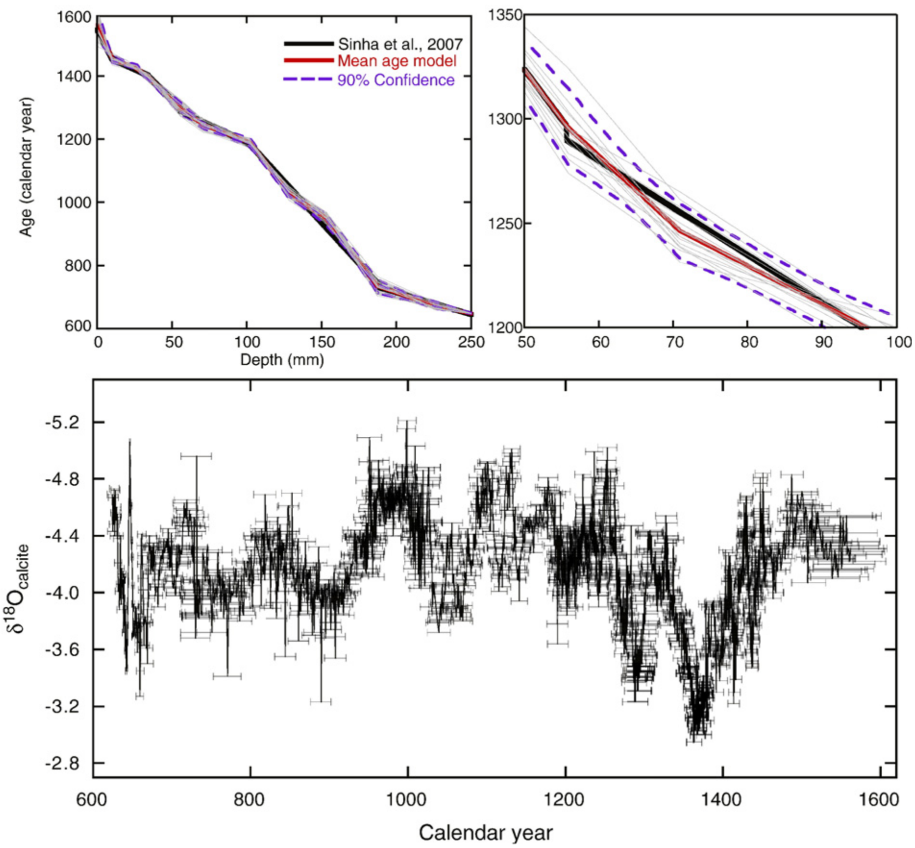

Fig. 2. Age model for the Dandak record, which was done using a Monte Carlo approach based on 12 U/Th dates (supplementary Table 3) in which we assume linear interpolation between dates and uncertainty to have a Gaussian distribution (left). See text for details on the dating and statistical methodologies. The mean age model is shown as a bold red line with 90% confidence intervals in purple. Numerous iterations of the simulation are shown as examples. The previous age model from Sinha et al. (2007) is shown in black. A close up section of the age model is exhibited to accentuate numerous age model iterations (center).The complete oxygen isotopic record from the Dandak Cave is shown with uncertainties in the *x*-direction (age). Uncertainties in the *y*-direction are assumed to be constant (0.15‰) as derived from the analytical uncertainty of the instrument. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of up to 0.81. The strong correlation between these two records on decadal timescales provides us not only with further confidence in our age model, but also assurance that our record reflects regional monsoon circulation and that common forcing mechanisms are likely acting to control precipitation amounts in these two distal locations.

Spectral analysis of the Dandak $\delta^{18}O$ record shows the presence of a single statistically significant peak that is centered around 90 years/cycle (Fig. 4). Although some of the age models show peaks at higher frequencies, such as a clustering around 25 yrs, no other peak retains significance when considered as a mean of all age models. When the

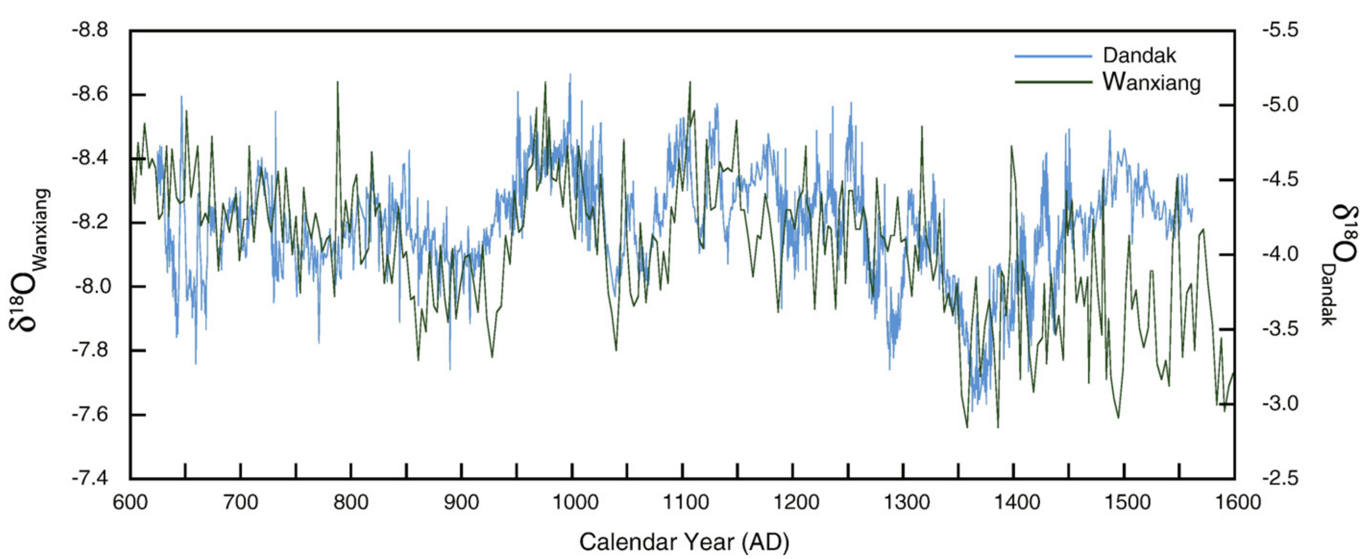

Fig. 3. The Dandak ISM record (using mean age model) and the Wanxiang cave Asian Summer monsoon record from China (Zhang et al., 2008).

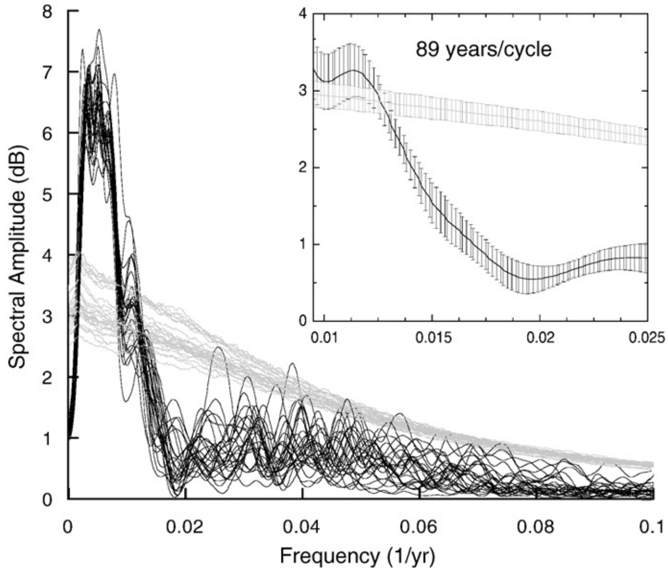

Fig. 4. Spectral analysis of the Dandak record using the Redfit Program (Schulz and Mudelsee, 2002). The black lines show the spectra for numerous iterations of the age model as described in the text and shown in the figure. The gray lines represent the upper 90% confidence limit of the red-noise alternative as determined with a Monte Carlo simulation.

record is filtered to capture only the variability within this temporal window, 8 manifestations of the cycle are clearly evident (Fig. 5). The amplitude of these cycles is, on average 0.5‰, which is half the range of $\delta^{18}O$ variability for the raw data (~1.0‰). The presence of power in this spectral band has previously been noted in a wide array of other proxy-monsoon reconstructions spanning the Holocene such as $\delta^{18}O$ stalagmite records from the Arabian Peninsula (Neff et al., 2001; Burns et al., 2002; Fleitmann et al., 2003) and China (Dykoski et al., 2005; Wang et al., 2005) and marine records from the Arabian and China Sea

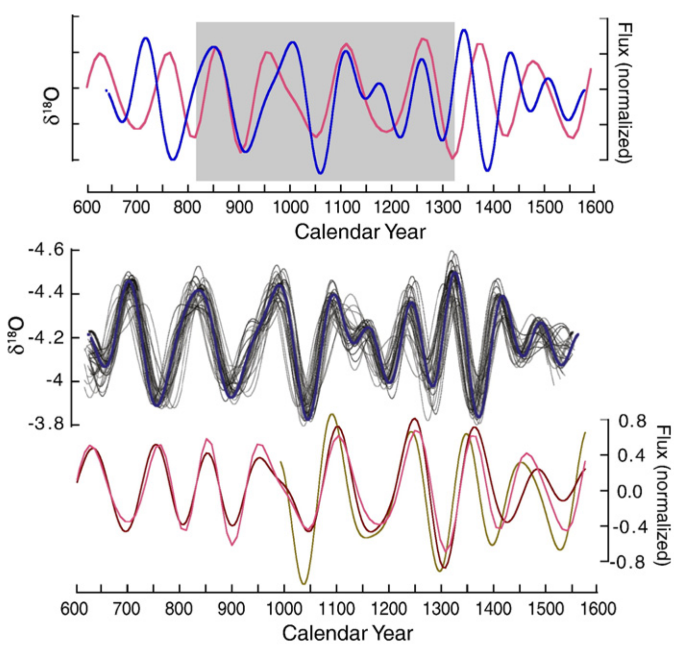

Fig. 5. Band-passed version of the Dandak record and normalized reconstructions of solar flux variability from Mann et al. (2005) (brown), Reimer et al. (2004) (pink) and Usoskin et al. (2008) (red). Numerous iterations of the age model are shown to illustrate the age uncertainty of our reconstruction (bottom). The top panel shows the mean age model and SFV reconstruction with the dark gray region delineating the period of time in which the ISM and SFV reconstructions are in-phase with one another.

(von Rad et al., 1999; Wang et al., 1999). The consistency of this signal in records from a wide region and the fact that its presence spans much of the Holocene, suggest a common forcing and one that is inherently persistent. All the aforementioned studies posit that the presence of this periodicity arises from the Gleissberg solar cycle, with a reported 88-year cycle as derived from numerous solar reconstructions (McCracken et al., 2001).

The precise chronology and high resolution of our record affords the opportunity to explore the solar origins of this cycle and not simply assume that a common spectral peak is indicative of causality. To test the assumption of causality, we explore the phase relationship of the ISM with SFV by comparing our $\delta^{18}O$ record with 3 independent solar reconstructions and assume that shared variance between the different reconstructions represents a conservative estimate for SFV. We do not attempt to apply a transfer function between solar variability and monsoon precipitation amounts and for this reason we were less concerned with absolute estimates of solar flux variance, which vary considerably between records (Crowley, 2000), and more that age uncertainty in the reconstruction was small enough to provide an accurate estimate for the timing of maxima and minima on decadal timescales. We chose to use the SFV record from 1) Mann et al. (2005), which was derived from ^{10}Be concentrations in Greenland ice cores, 2) Reimer et al. (2004), which was derived from residual-^{14}C in tree cores, and 3) the model of Usoskin et al. (2008) that considers the role of geomagnetic fluctuation in addition to residual-^{14}C measurements. Band-passed versions of the records shown in Fig. 5 clearly indicate common signals between these three independent reconstructions.

We envision four possible solar–monsoon relationships. In the simplest scenario the ISM and SFV would exhibit an in-phase relationship, which would suggest an instantaneous response between SFV and ISM. This relationship would imply that the SFV and ISM are linked through an atmospheric bridge either directly (e.g. (Kodera, 2004)) or through a modulator such as conditions in the ENSO domain (Emile-Geay et al., 2007). In the second scenario, there would be a consistent phase relationship but with a lag necessary for a change in solar flux to have an impact on monsoon circulation. In the third scenario, the phase relationship between the ISM and SFV is non-stationary, exhibiting transient periods of a coherent phase relationship. In this scenario, the impact of solar forcing on ISM is fleeting and governed by specific boundary conditions that promote the solar modulation of ISM. In the latter case, there is no solar–monsoon relationship and thus the common spectral properties are coincidental.

We observe that for most of the 1000 yrs that Dandak overlaps with the solar reconstructions, there is little coherence with the exception of the period between AD 800 and AD 1290 (Fig. 5). We are confident given our conservative treatment of age uncertainty that the change in the solar–monsoon relationship cannot simply be a function of uncertainties in the age model, as the maximum uncertainty in our age model during the transition intervals is less than 12 yrs (90% CI). Furthermore the high degree of resemblance between Dandak and Wanxiang Cave records, the latter having unprecedented low error on U–Th dates (Zhang et al., 2008), is further evidence of the robustness of our chronology during this interval. A tentative hypothesis to explain transient SFV–ISM coherence is that changes in the ocean-atmospheric system, specifically in the ENSO domain, acted to disrupt or enhance the SFV–monsoon bridge. This would imply that the dynamical mechanism linking ISM variability and SFV from Kodera (2004) is sensitive to external boundary conditions, which is an idea that is supported by the findings that ENSO may act as a modulator of solar flux variability (Emile-Geay et al., 2007). If so, a sustained change in ENSO dynamics during the MCA could have provided the conditions necessary for a consistent SFV–monsoon relationship. Indeed, a number of proxy records and modeling simulations indicate that anomalous ENSO conditions persisted during much of the MCA (Crowley, 2000; Cobb et al., 2003; Graham et al., 2007; Stott et al., 2004). If the ENSO-modulated solar forcing was the cause of strong solar–monsoon relationship during the MCA, the lack of a coherent relationship outside of this time interval indicates either varying ENSO dynamics and/or changing frequency and amplitude of IOD events, which can intermittently amplify or neutralize ENSO impact on monsoon circulation (Ashok et al., 2004).

Although we identify a feasible mechanism for a fleeting solar influence, it is not possible to show with statistical significance that the period of coherence is more than simply a product of two timeseries with similar spectral properties. We evaluate this further by trying to identify the presence of other higher frequency solar bands during the MCA interval, such as the well documented 11-year cycle. The spectral analysis provides no evidence of other known solar cycles acting to influence monsoon circulation during this period lending a further critique to a prominent solar-driven ISM during the MCA (Supplementary Fig. 1). Furthermore, if the solar cycle was only intermittent, it provides no causal explanation of the persistence of the 90-year cycle before and after this time window. These lines of evidence point towards a non-solar related mechanism driving the variability. The influence of North Atlantic SSTs on the ISM has been widely observed (Zhang and Delworth, 2006; Li et al., 2008; Yuan et al., 2008; Feng and Hu, 2008) and we thus consider it as the likely alternative in pacing the periodic multidecadal ISM variability. Evidence from the short instrumental record suggests a preferred multidecadal SST mode in the North Atlantic (Goswami et al., 2006), and proxy reconstructions from the region find evidence that a near-centennial cycle is inherent to the North Atlantic climate (Kerr, 2000; Appenzeller et al., 1998; Gray et al., 2004; Meeker and Mayewski, 2002). Modeling studies by Park and Latif (2008) have found that such a periodicity can arise internal to the north Atlantic system while Meeker and Mayewski (2002) suggest a transient solar influence of the North Atlantic that appears pronounced during periods of weak solar activity (e.g. AD 1400–1800). Contemporaneous hydroclimate proxy records from regions known to be influenced by North Atlantic climate such as Central America (Lachniet et al., 2004) and West Africa (Shanahan et al., 2009) also indicate significant peaks near 90 yrs. Given both their shared spectral properties and the established dynamical link, the North Atlantic emerges as the likely driver for persistence of multidecadal power of the ISM.

4. Conclusions

This study highlights the existence of a high-amplitude, recurrent, multidecadal scale pattern present in Indian summer monsoon rainfall during the MCA and adjacent centuries. Although the presence of such a feature has been observed from the short instrumental record, we provide compelling evidence for its persistence on longer timescales. The high amplitude of this cycle and that it apparently has a wide regional signature underscores the significance of this finding with respect to long-term forecasting of the ISM. For multiple centuries during the MCA this cycle appears paced by solar flux variations, which is consistent with the findings of previous work from the Arabian Peninsula (Fleitmann et al., 2003) and China (Zhang et al., 2008). We find that on both ends of the MCA, the relationship between solar flux and the ISM is no longer apparent. The change in relationship between ISM and SFV could mark a fundamental change in either ENSO and/or IOD behavior, which acted to disrupt this link. However, it is not possible to show with significance that this period of coherence is anything more than an artifact of two timeseries with similar spectra. We therefore, are inclined to interpret our record as evidence of a minimal role of solar variability in driving persistent multidecadal variability of the ISM. We have confidence based on both the previously established dynamical link and their shared spectral properties, that multidecadal variability of the North Atlantic SSTs plays the principal role in generating and maintaining this periodicity. The findings highlight two areas of research that require active exploration: (1) The need to extend high-resolution proxy records of the ISM to overlap with the instrumental record for the purposes of documenting the nature of multidecadal ISM variability during the Little Ice Age, which has unique boundary conditions relative to both the 20th century and MCA. (2) The apparent uniqueness of the MCA both from a standpoint of regional coherence and unique solar–ISM relationship highlights a demand for further studies on the dynamical anomalies during this period through modeling exercises, which will help unravel the coupled influences that ENSO, IOD, SFV and AMV have on the Indian monsoon system.

Acknowledgements

The authors would like to thank Miguel Rincon for the assistance in the stable isotope analysis, and A. Mangini, K. Anchukaitis and two anonymous reviewers for the helpful suggestions in improving the clarity of this paper. The work was supported by NSF grants to AS (ATM: 0823554), RLE and HC (ATM: 0502535) and Gary Comer Science and Education Foundation Grants CC8 and CP41 to RLE.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2009.12.017.

References

Agnihotri, R., Dutta, K., Bhushan, R., Somayajulu, B., 2002a. Evidence for solar forcing on the Indian monsoon during the last millennium. Earth Planet. Sci. Lett. 198.

Agnihotri, R., Ditta, K., Bhushan, R., Somayajulu, B., 2002b. Evidence for solar forcing on the Indian monsoon during the last millennium. Earth Planet. Sci. Lett. 198, 521–527.

Anderson, D.M., Overpeck, J.T., Gupta, A.K., 2002. Increase in the Asian southwest monsoon during the past four centuries. Science 297, 596–599.

Appenzeller, C., Stocker, T.F., Anklin, M., 1998. North Atlantic oscillation dynamics recorded in Greenland ice cores. Science 282, 446–449.

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

Bhattacharyya, S., Narasimha, R., 2005. Possible association between Indian monsoon rainfall and solar activity. J. Geophys. Res. 32. doi:10.1029/2004GL021044.

Bhattacharya, S.K., Froehlich, K., Aggarwal, P.K., Kulkarni, K.M., 2003. Isotopic variation in Indian Monsoon precipitation: records from Bombay and New Delhi. Geophys. Res. Lett. 30. doi:10.1029/2003GL018453.

Bryson, R., Swain, A., 1981. Holocene variations of monsoon rainfall in Rajasthan. Quatern. Res. 16, 135–145.

Burns, S.J., Fleitmann, D., Mudelsee, M., Neff, U., Matter, A., Mangini, A., 2002. A 780-year annually resolved record of Indian Ocean monsoon precipitation from a speleothem from south Oman. J. Geophys. Res. Atmos. 107. doi:10.1029/2001JD001281.

Cobb, K.M., Charles, C.D., Cheng, H., Edwards, R.L., 2003. El Nino/Southern Oscillation and tropical Pacific climate during the last millennium. Nature 424, 271–276.

Crowley, T., 2000. Causes of climate change over the past 1000 years. Science 289, 270–277.

Davis, M., Thompson, L., Yao, T., Wang, N., 2005. Forcing of the Asian monsoon on the Tibetan Plateau: evidence from high-resolution ice core and tropical coral records. J. Geophys. Res. 110.

Draxler, R.R., Rolph, G.D., 2003. HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) Model Access via NOAA ARL READY Website. NOAA Air Resources Laboratory, Silver Spring, MD. http://www.arl.noaa.gov/ready/hysplit4.html.

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.

Emile-Geay, J., Cane, M., Seager, R., Kaplan, A., Almasi, P., 2007. El Nino as a mediator of the solar influence on climate. Paleoceanography 22. doi:10.1029/2006PA001304.

Enzel, Y., Ely, L., Mishra, S., Ramesh, R., Amit, R., Lazar, B., Rajaguru, S., Baker, V., Sandler, A., 1999. A high-resolution Holocene environmental changes in the Thar desert, north-western India. Science 284, 125–128.

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. 35. doi:10.1029/2007GL032484.

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.

Gadgil, S., Rajeevan, M., Nanjundiah, R., 2005. Monsoon prediction — why yet another failure? Curr. Sci. 88, 1389–1400.

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.

Goswami, B., Xavier, P., 2005. ENSO control on the south Asian monsoon through the length of the rainy season. J. Geophys. Res. 32. doi:10.1029/2005GL023216.

Goswami, B.N., Madhusoodanan, M.S., Neema, C.P., Sengupta, D., 2006. A physical mechanism for North Atlantic SST influence on the Indian summer monsoon. Geophys. Res. Lett. 33. doi:10.1029/2005GL024803.

Graham, N., Hughes, M., Ammann, C., Cobb, K., Hoerling, M., Kennett, D., Kennett, J., Rein, B., Stott, L., Wigand, P., Xu, T., 2007. Tropical Pacific–mid-latitude teleconnections in medieval times. Clim. Change 45, 241–285.

Gray, S.T., Graumlich, L.J., Betancourt, J.L., Pederson, G.T., 2004. A tree-ring based reconstruction of the Atlantic Multidecadal Oscillation since 1567 AD. Geophys. Res. Lett. 31. doi:10.1029/2004GL019932.

Gupta, A., Anderson, D., Overpeck, J., 2003. Abrupt changes in the Asian southwest monsoon during the Holocene and their links to the North Atlantic Ocean. Nature 421, 354–357.

Haigh, J., 1996. The impact of solar variability on climate. Science 272, 616–636.

Hoyos, C.D., Webster, P.J., 2007. The role of intraseasonal variability in the nature of Asian monsoon precipitation. J. Climate 20, 4402–4424.

Kar, R., Ranhotra, P., Bhattacharyya, A., Sekar, B., 2002. Vegetation vis-à-vis climate and glacial fluctuations of the Gangotri glacier since the last 2000 years. Curr. Sci. 82, 347–351.

Kerr, R.A., 2000. A North Atlantic climate pacemaker for the centuries. Science 288, 1984–1986.

Kodera, K., 2004. Solar influence on the Indian Ocean Monsoon through dynamical processes. Geophys. Res. Lett. 31. doi:10.1029/2004GL020928.

Kumar, K.K., Rajagopalan, B., Hoerling, M., Bates, G., Cane, M., 2006. Unraveling the mystery of Indian monsoon failure during El Nino. Science 314, 115–119.

Lachniet, M.S., Burns, S.J., Piperno, D.R., Asmerom, Y., Polyak, V.J., Moy, C.M., Christenson, K., 2004. A 1500-year El Nino/Southern Oscillation and rainfall history for the Isthmus of Panama from speleothem calcite. J. Geophys. Res. Atmos. 109. doi:10.1029/2004JD004694.

Li, S.L., Perlwitz, J., Quan, X.W., Hoerling, M.P., 2008. Modelling the influence of North Atlantic multidecadal warmth on the Indian summer rainfall. Geophys. Res. Lett. 35. doi:10.1029/2007GL032901.

Luo, J.J., Behera, S., Masumoto, Y., Sakuma, H., Yamagata, T., 2008. Successful prediction of the consecutive IOD in 2006 and 2007. Geophys. Res. Lett. 35. doi:10.1029/2004JD004933.

Maharatna, A., 1996. The Demography of Famines: An Indian Historical Perspective. Oxford Univ. Press, New Delhi, 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. Climate 18, 447–456.

McCracken, K.G., Dreschhoff, G.A.M., Smart, D.F., Shea, M.A., 2001. Solar cosmic ray events for the period 1561–1994 2. The Gleissberg periodicity. J. Geophys. Res. Space Phys. 106, 21599–21609.

Meehl, G., Arblaster, J., Matthes, K., Sassi, F., van Loon, H., 2009. Amplifying the Pacific climate system response to a small 11-year solar cycle forcing. Science 325, 1114–1118.

Meeker, L.D., Mayewski, P.A., 2002. A 1400-year high-resolution record of atmospheric circulation over the North Atlantic and Asia. Holocene 12, 257–266.

Mudelsee, M., Scholz, D., Röthlisberger, R., Fleitmann, D., Mangini, A., Wolff, E.W., 2009. Climate spectrum estimation in the presence of timescale errors. Nonlin. Processes Geophys. 16, 43–56.

Neff, U., Burns, S.J., Mangini, A., Mudelsee, M., Fleitmann, D., Matter, A., 2001. Strong coherence between solar variability and the monsoon in Oman between 9 and 6 kyr ago. Nature 411, 290–293.

Park, W., Latif, M., 2008. Multidecadal and multicentennial variability of the meridional overturning circulation. Geophys. Res. Lett. 35. doi:10.1029/2008GL035779.

Phadtare, N., Pant, R., 2006. A century-scale pollen record of vegetation and climate history during the past 3500 years in the Pinder Valley, Kumaon Higher Himalaya. India J. Geol. Soc. India 68, 495–506.

Prasad, S., Kusumgar, S., Gupta, S.K., 1997. A mid to late Holocene record of palaeoclimatic changes from Nal Sarovar: a palaeodesert margin lake in western India. J. Quatern. Sci. 12, 153–159.

Rajeevan, M., Sridhar, L., 2008. Inter-annual relationship between Atlantic sea surface temperature anomalies and Indian summer monsoon. Geophys. Res. Lett. 35. doi:10.1029/2008GL036025.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, G., Manning, S., Ramsey, C.B., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. IntCal04 terrestrial radiocarbon age calibration, 0–26 cal kyr BP. Radiocarbon 46, 1029–1058.

Sarkar, A., Ramesh, B., Somayajulu, R., Agnihotri, R., Jull, A., Burr, G.S., 2000. High resolution Holocene monsoon record from the eastern Arabian Sea. Earth Planet. Sci. Lett. 177, 209–218.

Schulz, M., Mudelsee, M., 2002. REDFIT: estimating red-noise spectra directly from unevenly spaced paleoclimatic time series. Comp. Geosci. 28, 421–426.

Schulz, M., Stattegger, K., 1997. SPECTRUM: spectral analysis of unevenly spaced paleoclimatic time series. Comp. Geosci. 23, 929–945.

Shanahan, T.M., Overpeck, J.T., Anchukaitis, K.J., Beck, J.W., Cole, J.E., Dettman, D.L., Peck, J.A., Scholz, C.A., King, J.W., 2009. Atlantic forcing of persistent drought in West Africa. Science 324, 377–380.

Sharma, S., Joachimski, M., Tobschall, H., Singh, H., Sharma, C., Chauhan, M., Morgenroth, G., 2004. Late glacial and Holocene environmental changes in Ganga plain, northern India. Quatern. Sci. Rev. 23, 145–159.

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. doi:10.1029/2007GL030431.

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

Stott, L., Cannariato, K., Thunell, R., Haug, G.H., Koutavas, A., Lund, S., 2004. Decline of surface temperature and salinity in the western tropical Pacific Ocean in the Holocene epoch. Nature 431, 56–59.

Usoskin, I.G., Korte, M., Kovaltsov, G.A., 2008. Role of centennial geomagnetic changes in local atmospheric ionization. Geophys. Res. Lett. 35. doi:10.1029/2007GL033040.

von Rad, U., Schaaf, M., Michels, K.H., Schulz, H., Berger, W.H., Sirocko, F., 1999. A 5000-yr record of climate change in varved sediments from the oxygen minimum zone off Pakistan, northeastern Arabian Sea. Quatern. Res. 51, 39–53.

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

Wang, B., An, S., 2002. A mechanism for decadal changes of ENSO behavior: roles of background wind changes. Climate Dynamics 18, 475–486.

Wang, L., Sarnthein, M., Erlenkeuser, H., Grimalt, J.O., Grootes, P., Heilig, S., Ivanova, E., Kienast, M., Pelejero, C., Pflaumann, U., 1999. East Asian monsoon climate during the Late Pleistocene: high-resolution sediment records from the South China Sea. Mar. Geol. 156, 245–284.

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.

Webster, P., 1987. The elementary monsoon. In: Fein, J., Stephens, P. (Eds.), Monsoon. John Wiley, New York.

Yadav, R., Singh, J., 2002. Tree-ring-based spring temperature patterns over the past four centuries in western Himalaya. Quatern. Res. 57, 299–305.

Yadava, M.G., Ramesh, R., Pant, G.B., 2004. Past monsoon rainfall variations in peninsular India recorded in a 331-year-old speleothem. Holocene 14, 517–524.

Yuan, Y., Chan, C.L.J., Wen, Z., Li, C.Y., 2008. Decadal and interannual variability of the Indian Ocean dipole. Adv. Atmos. Sci. 25, 856–866.

Zhang, R., Delworth, T.L., 2006. Impact of Atlantic multidecadal oscillations on India/Sahel rainfall and Atlantic hurricanes. Geophys. Res. Lett. 33. doi:10.1029/2006GL026267.

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.