of fire in areas that are undergoing substantial land-use changes or are subject to widespread biological invasions (e.g., cheatgrass in the Great Basin of the United States).

Currently, the spatial distribution models of fire activity described here have primarily been used to explore the occurrence of fires, yet other fire regime elements will be important to include in future work. Fire seasonality, intensity, area burned, and frequency are all elements of a fire regime, and all of these characteristics could be expected to shift under past or future climates. Overall, the pyrogeography framework provides a foundation for quantifying the causes and effects of fire regimes, which is critical to understanding fire-related ecosystem function, carbon dynamics and atmospheric chemistry.

References

Higuera, P., Brubaker, L., Anderson, P., Hu F. and Brown, T., 2009: Vegetation mediated the impacts of postglacial climate change on fire regimes in the south-central Brooks Range, Alaska, *Ecological Monographs*, **79**: 201–219.

Krawchuk, M.A. and Moritz, M.A., 2009: Fire regimes of China: inference from statistical comparison with the United States, *Global Ecology and Biogeography*, **18**: 626–639.

Krawchuk, M.A., Moritz, M.A., Parisien, M.-A., Van Dorn, J. and Hayhoe, K., 2009: Global pyrogeography: the current and future distribution of wildfire, *PLoS ONE*, **4**: e5102.

Parisien, M.-A. and Moritz, M.A., 2009: Environmental controls on the distribution of wildfire at multiple spatial scales, *Ecological Monographs*, **79**: 127–154.

Westerling, A. and Bryant, B., 2008: Climate change and wildfire in California, *Climatic Change*, **87**: 231–249.

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Emerging proxy evidence for coherent failures of the summer monsoons of Asia during the last millennium

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New high resolution speleothem and tree ring records show evidence for spatially widespread Asian monsoon megadroughts during the last millennium.

No annually recurring weather phenomena on Earth influence the lives of as many people as the regional summer monsoons of Asia. Agricultural output and consequently food security across Asia is largely dependent on the timely arrival and adequate amounts of monsoon rainfall. Groundwater resources are often the only safeguard against monsoon failure and their rapid depletion signifies an increased vulnerability to monsoon deviations (Rodell et al., 2009). To a first order, the poleward march of the inter-tropical convergence zone during the boreal summer leads to a large amount of rainfall across the "Monsoon Asia". However, in years when the monsoon circulation and precipitation amount departs from its "normal" spatiotemporal patterns, it can have significant adverse societal impacts. Our current understanding of the variability of the regional summer monsoons of Asia is primarily gleaned from the instrumental record, which is too short to confidently assess the potential end-member hydroclimate scenarios of the monsoon system. Some of the longest instrumental records (starting ca. 1850s AD) from India show that, barring a few sporadic occurrences of monsoon failure (defined by the Indian Meteorology Department as JJAS rainfall >20% below the mean), year-to-year variations in the Indian monsoon rainfall have remained generally within 10% of its long-term climatological mean. However, historic documentary evidences from the region point to the occurrence of extended spells of substantially reduced monsoon rainfall before the instrumental record began (Maharatna, 1996).

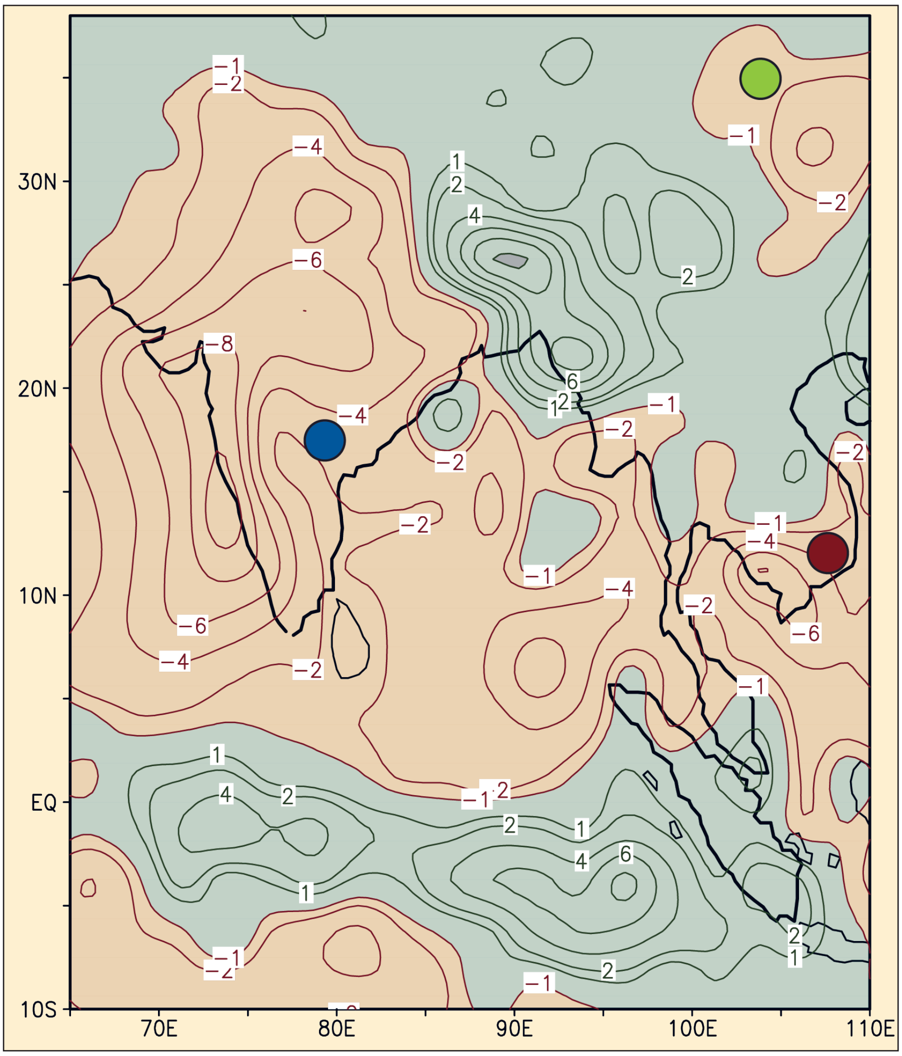

*Figure 1: Map showing locations of sites mentioned in the text and Figure 2; **Green circle** = Wanxiang, **blue circle** = Dandak, **brown circle** = Bidoup Nui Ba National Park. Contours and shading indicate July and August precipitation anomalies (mm/day) with respect to 1971-2000 interval (**red** = drier, **blue** = wetter) during the major monsoon break spells in 2002 and 2004. Rainfall data are from the Climate Prediction Center Merged Analysis of Precipitation.*

The present day water resource infrastructure and the contingency planning in Monsoon Asia, as informed by instrumental observations, does not take into account the possibility of protracted failures of the monsoon. A longer-term assessment of monsoon variability is crucial to identify the full frequency spectrum of monsoon behavior. This should be developed from a spatially expansive network of precipitation, circulation, and drought sensitive proxy records, spanning the last several centuries to millennia, at resolutions comparable to the instrumental record. In this text, we highlight how an emerging network of proxy records from Asia is unraveling previously unknown aspects of monsoon behavior during the last millennium. Manifested in these proxy records is an evolving picture of monsoon's natural variability, including the repeated tendency to get locked in extended dry and wet phases.

Recent proxy records of Asian summer monsoons

Speleothem-based oxygen isotopic ($\delta^{18}O$) records have previously yielded a remarkably coherent depiction of how the monsoon systems of Asia have varied on orbital and millennial timescales (Wang et al., 2008). In monsoonal regions, the empirical inverse relationship between the $\delta^{18}O$ of precipitation and precipitation amount (the amount effect) forms the basis of these reconstructions. This approach however, has not been rigorously applied to the reconstruction of monsoon variability over the last 1-2 millennia. This is due in part, to the notion that the amplitude of late Holocene climate-related $\delta^{18}O$ change in the speleothem would be too small to be discernible from the "noise" produced from local karst and non-climate related processes.

A sub-annually resolved speleothem $\delta^{18}O$ record from Dandak Cave in central India serves as a test of this approach (Fig. 1). This site, by virtue of its location, is characterized by a strong amount effect and the local monsoon precipitation is strongly correlated with the area-averaged precipitation over much of India (Sinha et al., 2007). The near millennial-length $\delta^{18}O$ record (AD 600 and 1500) reveals prominent multi-decadal scale variability in the Indian summer monsoon precipitation with a ~90 year period comparable to that inferred from the instrumental record (Berkelhammer et al., 2010). The $\delta^{18}O$ record also provides evidence for years to decades-long intervals of substantially reduced monsoon rainfall, such as during portions of the 7th, 9th, 11th, 13th, 14th and early 15th centuries (Fig. 2). The observed amount effect relationship for this region suggests that some of these droughts were marked by a reduction in monsoon rainfall amount (relative to the 20th century climatological mean) of up to 20 to 30 %, and at least one drought during the latter half of the 14th century may have lasted as long as 30 years (Sinha et al., 2007). These inferred monsoon failures, most of which are independently corroborated with historical accounts of famine in India, have no analog in the instrumental record.

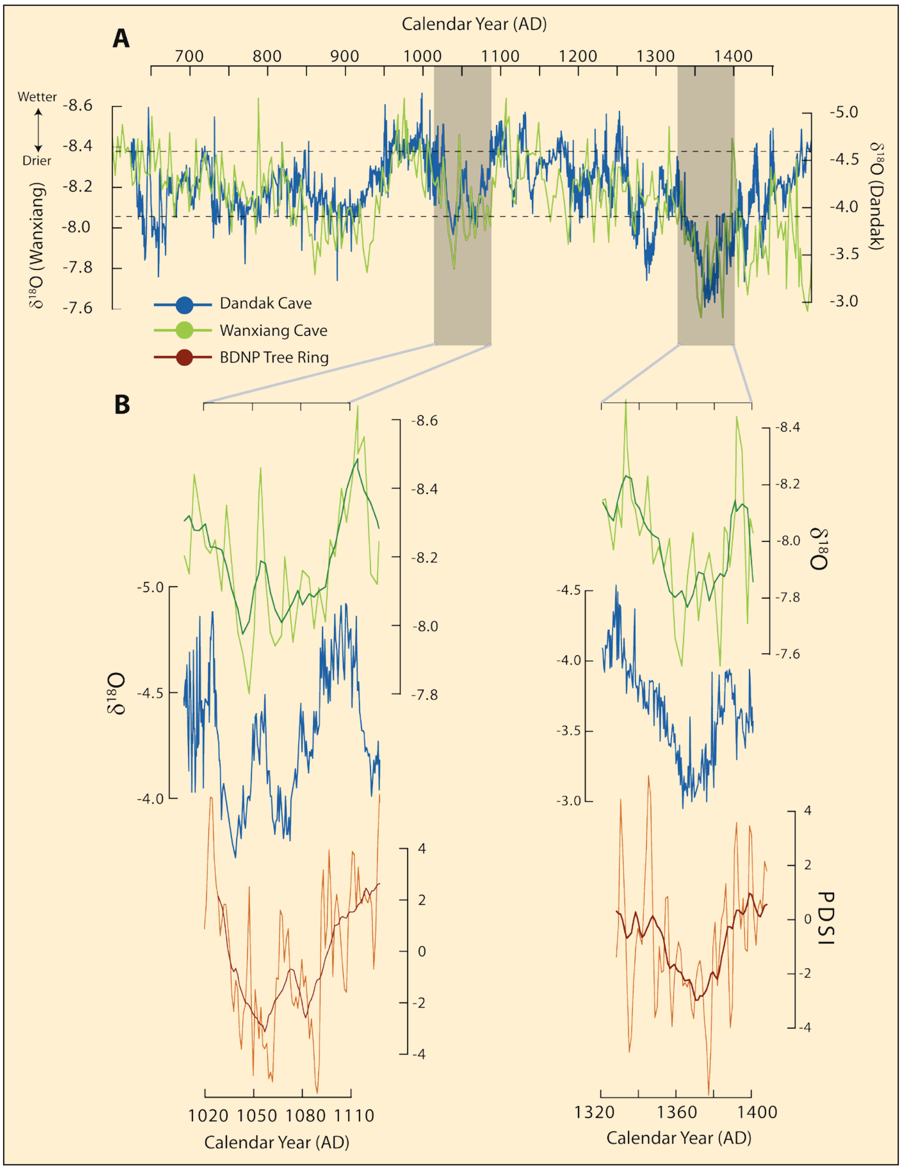

*Figure 2: Recent proxy records from monsoon Asia. **A**) Comparison of Dandak Cave $\delta^{18}O$ record with the overlapping portion of the Wanxiang Cave $\delta^{18}O$ record. The range of modern $\delta^{18}O$ values of calcite in Dandak Cave is shown by two dashed lines. The $\delta^{18}O$ values higher than -3.8 ‰ delineate intervals of inferred drought and imply more than 10% decrease in monsoon months (JJAS) rainfall. Gray bars indicate two extended periods of inferred drought. **B**) Comparison between the speleothem $\delta^{18}O$ records and Vietnam's Bidoup Nui Ba National Park (BDNP) tree-ring Palmer Drought Severity Index (PDSI) (March-May) reconstruction for the two extended intervals of drought. Dark lines show running mean averages.*

A high-resolution speleothem $\delta^{18}O$ record from the Wanxiang Cave in central China (Fig. 1), which reveals broad-scale changes in the East Asian summer monsoon during the past two millennia (Zhang et al., 2008), bears a striking resemblance with the $\delta^{18}O$ record from India (Fig. 2). Together, these two speleothem records provide not only assurance of the timing and magnitude of drought events but also suggest that these extended intervals of weaker monsoon were in fact synchronous across a large region of Asia. This assertion is strongly supported by a new tree ring-width based Palmer Drought Severity Index (PDSI) record from Bidoup Nui Ba National Park (BDNP) in southern Vietnam (Fig. 1; Buckley et al., 2010). This PDSI record, reflecting the SE Asian monsoon variability during the last millennium, is notable because thus far, comprehensive dendroclimatology has rarely been applied in the core monsoon regions of Asia due, in part, to the notion that trees in these regions lack clear annual rings, and also poor understanding of phenology and physiology of the tree species, and large-scale deforestation in the region (Buckley et al., 2007).

The comparison of overlapping portions of the PDSI and speleothem $\delta^{18}O$ records highlights two extended intervals of region-wide weaker monsoon during the 11th and mid 14th/early 15th centuries (Fig. 2). In particular, the latter interval stands out as one marked by significant societal change across monsoon Asia, which included famines and significant political reorganization within India (Sinha et al., 2007), the collapse of the Yuan dynasty in China (Zhang et al, 2008); and the Khmer civilization of Angkor Wat fame in Cambodia (Buckley et al., 2010). Although the relationship between climate and societal change is complex and not necessarily deterministic, the close temporal association between droughts and widespread societal changes across monsoon Asia at that time strongly suggests that monsoon droughts may have played a major role in shaping these societal changes.

Conclusion

The case for synchronous droughts in recent monsoon reconstructions across widely separated regions is compelling and suggests that the monsoon circulation in Asia can "lock" into a drought-prone mode that may last for years to decades. Understanding the ocean-atmosphere dynamics that trigger such droughts is important in order to anticipate the likelihood of their reoccurrence today. The spatiotemporal patterns of monsoon rainfall over Asia are complex and vary from year to year (Fig. 1). This complexity stems from interactions between rain-bearing synoptic-scale systems, which are propagated from the oceans onto the land, mid-latitude weather systems, ocean-atmosphere dynamics over the Equatorial Indian Ocean, and the Walker circulation in the tropical Pacific. Periodic perturbations in coupled modes of ocean-atmosphere variability, such as the El Niño Southern Oscillation, and/or dynamical processes intrinsic to the monsoon system such as quasi-periodic episodes of intense ("Active") and reduced ("Break") monsoon rainfall, are key processes that are known to orchestrate substantial precipitation anomalies over large parts of Asia. The societal implications of these new findings suggest that the narrow view of the monsoon taken from the instrumental data alone may lull us into a false sense of security. Thus a longer term and a fuller range of monsoon variability, as documented in the recent proxy records, should be urgently incorporated into future drought management and mitigation planning.

References

Berkelhammer, M., Sinha, A., Mudelsee, M., Cheng, H., Edwards, L. and Cannariato, K. G., 2010: Persistent Multidecadal Power in the Indian Summer Monsoon, *Earth and Planetary Science Letters*, **290**: 166–172.

Buckley, B.M., Palakit, K., Duangsathaporn, K., Sanguantham, P. and Prasomsin, P., 2007: Decadal scale droughts over northwestern Thailand over the past 448 years: links to the tropical Pacific and Indian Ocean sectors, *Climate Dynamics*, **29**: 63–71.

Buckley, B.M., Anchukaitis, K.J., Penny, D., Fletcher, R., Cook, E.R., Sano, M., Nam, L.C., Wichienkeeo, A., Minh, T.T. and Hong, T.M., 2010: Climate as a contributing factor in the demise of Angkor, Cambodia, *Proceedings of the National Academy of Science*, doi: 10.1073/pnas.0910827107.

Sinha, A., Cannariato, K.G., Stott, L.D., Cheng, H., Edwards, R.L., Yadava, M.G., Ramesh, R. and 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, *Geophysical Research Letters*, **34**: L16707.

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

For full references please consult:

http://www.pages-igbp.org/products/newsletters/ref2010_2.html

An emerging paradigm: Process-based climate reconstructions

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Emerging techniques and concepts offer ways to improve the use of process knowledge in reconstructions of past climate, and to make more comprehensive estimates of the uncertainties associated with them.

The last few decades have seen extraordinary progress in the reconstruction of past climates using natural and human archives (Jones et al., 2009; Wanner et al., 2008). At the same time, our understanding of the climate system has deepened, strongly motivating development of new methods of integrating observations and model analyses. To continue this progress, it would be desirable to use all the climate information we can extract from natural archives. Frequently, only those aspects of the records are used that lend themselves to linear transformation into estimates of conventional climate quantities, such as mean seasonal temperatures or seasonal totals of precipitation. However, one can readily point to robust climatic information in natural archives that does not fit conveniently into a linear regression model (e.g., see Kelly et al., 1989). A way forward is offered by increased use of process-based forward models that capture the main features of the environmental control of the formation of natural archives (Fig. 1).

Focus on process

Each proxy archive represents a record of climate that was generated through physical, chemical and/or biological processes. Reconstructions of climate represent attempts to turn this around in order to get back to the climate information. Statistical solutions (most often regression) are used to identify simple, usually linear, relationships over a period covered by both proxy and instrumental climate records. This approach therefore reduces the problem to identifying a single climatic driver of the local proxy record stored in the natural archive, a driver that is assumed to be dominant at all times.

Two recent articles (Guiot et al., 2009; Hughes and Ammann, 2009) discuss converging trends in the use of modern understanding of proxy-forming processes. They point to important emerging tools and capabilities in exploring climates of the past that could help avoid the limitations of current empirical-statistical methods.

Guiot et al. (2009) focused on the Holocene and the Last Glacial Maximum, periods spanning major shifts in both forcing and the state of the climate system. Emphasizing paleovegetation records, Guiot et al. (2000) proposed a move from empirical-statistical models to the inversion of forward models of the formation of such natural archives (Fig. 1). For sediment data with relatively low accumulation rates, the current statistical solution is to use spatial data to calibrate a relationship between proxy and climate and to apply this "space-for-time" relationship to information on past vegetation so that the climate can be inferred. This approach assumes that the laws producing the natural archive remained constant throughout space and time (uniformitarian principle). However, when non-climatic factors such as atmospheric CO_2 concentration have changed during the period analyzed or with respect to the present, this assumption may have been violated. This is a major motivation for moving towards process-based models to better capture vegetation changes according to a realistic set of all major forcing variables, whether climatic or not.