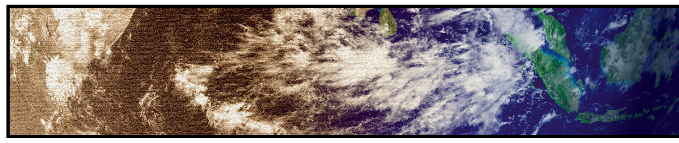

Monsoon climate - Will summer rain increase or decrease in monsoon regions?

PRESENT

Bin Wang
Department of Meteorology and International Pacific Research Center, University of Hawaii, Honolulu, USA; wangbin@hawaii.edu

In physical essence, monsoon is a forced response of the coupled climate system to the annual cycle of insolation. Land-sea thermal contrast, moisture processes, topography and Earth's rotation are critical in determining monsoon rainfall patterns and vigor. Integrated regional monsoons generate a global-scale seasonally varying overturning circulation throughout the tropics (Trenberth et al. 2000). Global monsoon (GM) represents the dominant mode of annual variation of the tropical precipitation and circulation (Wang and Ding 2008), thus a defining feature of seasonality and a major mode of variability of the Earth's climate system.

Monsoon climate features an annual reversal of surface winds and contrasting rainy summer and dry winter. The monsoon domains defined by precipitation characteristics are shown in Figure 1, which include all regional monsoons over South Asia, East Asia, Australia, Africa and the Americas (Wang and Ding 2008).

Monsoonal interannual-interdecadal variations have been studied primarily on regional scales due to their indigenous characteristics associated with specific land-ocean configuration and differing feedback processes. However, global observations over the past three decades reveal a cohesive interannual variation across regional monsoons driven by El Niño-Southern Oscillation (ENSO). Thus, regional monsoons are coordinated not only by external (e.g. orbital) forcing but also by internal feedback processes, such as ENSO.

To what extent the regional monsoons vary in a cohesive manner on interdecadal time scale remains elusive. So far no uniform trend or coherent variation pattern has been found over the global monsoon domain. The total amount of global land monsoon rainfall during 1948-2003 exhibits an interdecadal fluctuation with a decreasing trend mainly due to weakening West African and South Asian monsoons (Zhou et al. 2008; Wang et al. 2011). But, since 1980 the global land monsoon rainfall has no significant trend, while the global oceanic monsoon precipitation shows an increasing trend (Wang et al. 2011).

A millennial simulation with the coupled climate model ECHO-G forced by changes in solar radiation, volcanic aerosols and greenhouse gas (GHG) concentration provides useful insight to GM rainfall variability. The leading pattern of centennial variability (wet Medieval Climate Anomaly, dry Little Ice Age, and wet present warming period) is characterized by a nearly uniform increase of precipitation across all regional monsoons, which is a forced response to the changes in external solar-volcanic and GHG forcing (Liu et al., unpublished data). The increase of GSMP is sensitive to warming pattern and determined by enhanced (a) land-ocean thermal contrast, (b) east-west thermal contrast between Southeast Pacific and tropical Indian Ocean, and (c) circumglobal southern hemisphere subtropical highs, which contribute to the hemispherical thermal contrast (Lui et al., unpublished data).

Will summer monsoon rain increase or decrease in the future? Based on the IPCC AR4 (Meehl et al. 2007), during austral summer the rainfall in all SH monsoon regions tends to increase (Fig. 1) and during boreal summer the rainfall in NH monsoon regions will also increase except for North America where it will decrease (Fig. 1). Thus, an overall intensification of summer monsoon rainfall is projected, signifying an amplifying annual variation of the hydrological cycle. Meanwhile the precipitation in the global subtropical desert and trade wind regions will decrease due to a monsoon-desert coupling mechanism. The annual mean monsoon precipitation is projected to increase in Asian-Australian monsoon but decrease in Mexico and Central America. However, the uncertain role of aerosols in general and carbon aerosols in particular, complicates future projections of monsoon precipitation over land, especially for Asia. Further understanding of the driving mechanisms behind monsoon changes holds a key for their reliable prediction.

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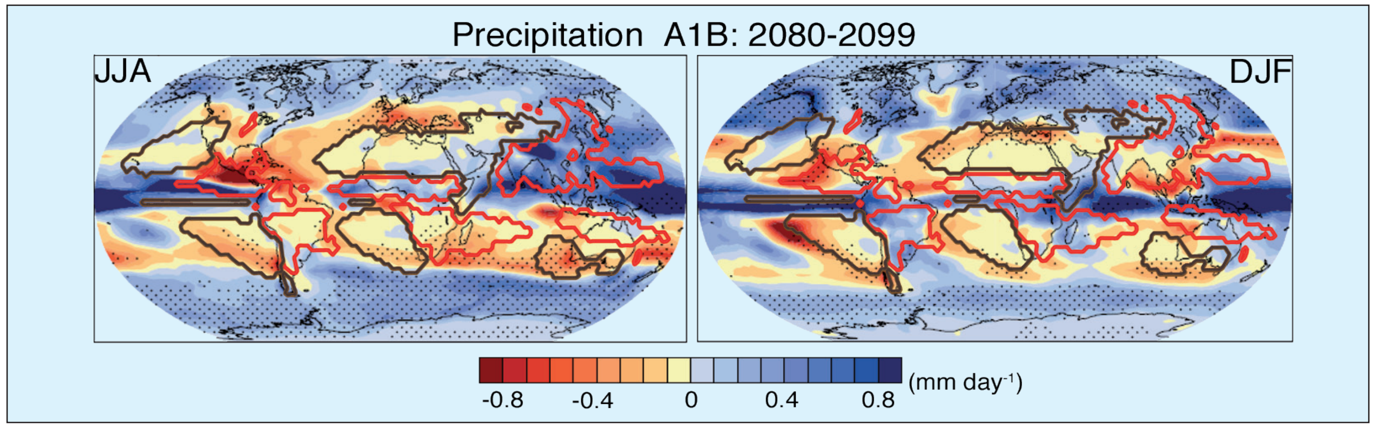

Figure 1: Multi-model mean changes in precipitation for boreal winter (DJF) and summer (JJA). Changes are given for the SRES A1B scenario, for the period 2080 to 2099 relative to 1980 to 1999. Stippling denotes areas where the magnitude of the multi-model ensemble mean exceeds the inter-model standard deviation. In the global monsoon domain (red contours) the summer-minus-winter precipitation exceeds 2.5 mm/day and the summer precipitation exceeds 55% of the annual total (Wang and Ding 2008). The dry regions with summer precipitation <1 mm/day are outlined in gray. The merged Global Precipitation Climatology Project/Climate Prediction Center Merged Analysis of Precipitation data were used to determine the monsoon and arid regions.

PAST

Hai Cheng[1,2], Ashish Sinha[3] and Steven M. Colman[4]
[1]Institute of Global Environmental Change, Xi'an Jiaotong University, Xi'an, China; cheng021@umn.edu
[2]Department of Earth Sciences, University of Minnesota, Minneapolis, USA; [3]Department of Earth Science, California State University, Carson, USA; [4]Large Lakes Observatory, University of Minnesota, Duluth, USA

Arab sailors, who traded extensively along the coasts of Arabia and India, used the word *mausim*, which means "seasons", to describe the large-scale changes in the winds over the Arabian Sea. The word "monsoon" likely originated from *mausim* and today it is applied to describe the tropical-subtropical seasonal reversals in the atmospheric circulation and associated precipitation over Asia-Australia, the Americas, and Africa.

The regional monsoons have long been viewed as gigantic, thermally-driven, land-sea breezes (Wang 2009). With the advent of satellite-based observations, a holistic view of monsoon has emerged which considers regional monsoons to be interactive components of a single global monsoon (GM) system. The GM is coordinated primarily by the annual cycle of solar radiation and the corresponding reversal of land-sea temperature gradients, along with the seasonal march of the Intertropical Convergence Zone (ITCZ).

A vast body of data describing "paleomonsoons" (PM) has been assembled from proxy archives, such as ice cores, marine and lake sediments, pollen spectra, tree-rings, loess, speleothems, and documentary evidence. Different archives record different aspects of the PM, and most are subject to complications such as thresholds in the climate or recording systems. In most cases it is difficult to extract detailed paleo-seasonality information (e.g. length or precipitation amounts of the summer rainy season) from such archives. Nonetheless, the proxy records describe PM variations on the time scales permitted by sample resolutions and chronologic constraints.

The PM phenomenon can be traced back to the deep time (10^6 to 10^8 years) (Wang 2009), but much focus has been put on reconstructing PM on orbital to decadal scales. Although the mechanisms driving PM oscillations are quite distinct on different time scales, the spatial-temporal patterns of PM variability are indeed comparable to the observed annual variations of the modern GM. For example, glacial-interglacial PM variability has been shown to be driven primarily by changes in summer insolation and global ice volume, and was possibly modulated by cross-equatorial pressure gradients (An et al. 2011). On orbital scales, PMs oscillated between strong states (during high summer insolation) and weak states (during low summer insolation), respectively, hence exhibiting an anti-phase relationship between the two hemispheres (Fig. 1, left panel).

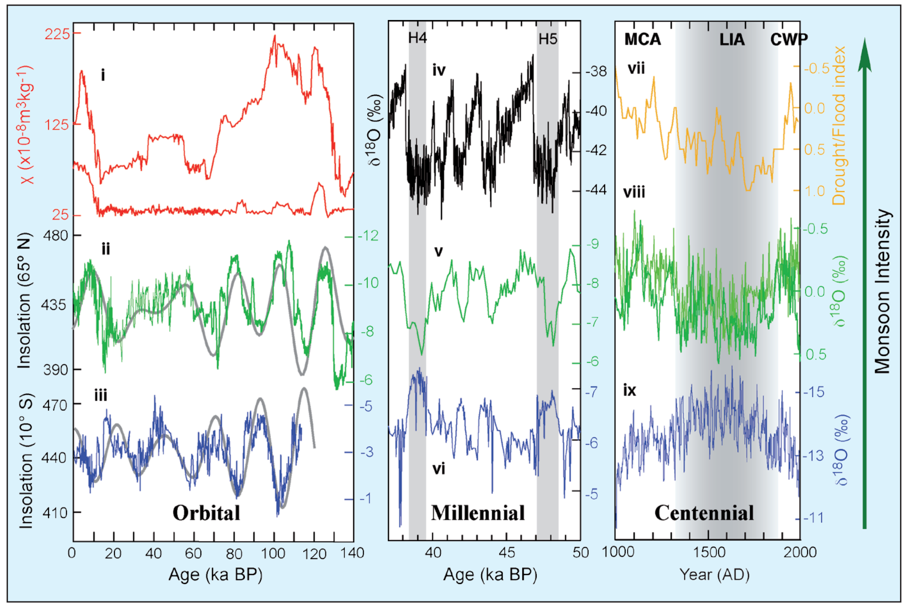

*Figure 1: Paleo-monsoon variability on orbital (**left**), millennial (**middle**) and centennial (**right**) time scales. (**i**) Chinese loess magnetic susceptibility (Sun et al. 2006) reflects AM glacial-interglacial variablility. (**ii**) Speleothem oxygen isotope ($\delta^{18}O$) records from China (Wang et al. 2008) and (**iii**) SE Brazil (Cruz et al. 2005) illustrate precessional cyclicity that follows summer insolation in their respective hemispheres (gray curves; Berger 1978) and anti-phasing between the AM and the SAM. (**iv**) Greenland ice core $\delta^{18}O$ as a temperature approximation (Svensson et al. 2008). (**v**) Speleothem $\delta^{18}O$ for AM (Wang et al. 2008) and (**vi**) SAM from northern Peru (Cheng et al., unpublished). Periods of Greenland warmth correspond with intense AM but are anti-phased with SAM intensity. (**vii**, **viii**) AM records from the summer monsoon fringes in China. (**vii**) Longxi Drought/Flood index based on historical literatures (Tan et al. 2011). (**viii**) Wangxiang (Zhang et al. 2008) and Huangye (Tan et al. 2011) speleothem records. (**ix**) Pumacocha lake record from Peru (Bird et al. 2011). MCA=Medieval Climate Anomaly; LIA=the Little Ice Age; CWP=Current Warm Period; H4 and H5 = Heinrich stadials.*

A number of proxy records of PM from both hemispheres reveal characteristic millennial-centennial length variability (Fig. 1, middle and right panel). On these time scales, PM oscillated between two contrasting states, with weak PM in the Northern and strong PM in the Southern Hemisphere and *vice-versa*. This pattern conforms remarkably well to climate model simulations that link changes in PM with changes in the Atlantic Meridional Overturning Circulation, which result in changes in interhemispheric temperature contrast and in turn, the mean latitudinal location of the ITCZ.

Human cultural history in monsoon regions is rich with accounts of severe climatic impacts related to changes in monsoon rainfall. Indeed, annually-resolved proxy records of PM covering the last few millennia reveal marked decadal-scale changes in spatiotemporal patterns of rainfall that are clearly outside the range of instrumental measurements of monsoon variability (e.g. Zhang et al. 2008; Bird et al. 2011; Tan et al. 2011; Sinha et al. 2011).

Most proxy studies indicate that PM strength across a range of time scales was modulated by near-surface land-sea thermal contrasts. However, the Asian Monsoon (AM) at its fringes and the South American Monsoon (SAM) seem to have waned over the past 50-100 years (Fig. 1, right panel). This is anomalous in the context of global warming, which presumably increases summer land-sea thermal contrasts and thus intensifies summer monsoons. If the observed waning trend of summer monsoon in fringe regions is linked to global warming over the last century and the total moisture evaporated from ocean increases in a future warmer world, one may expect persistent weaker summer monsoons in fringe areas of the monsoon, along with increased rainfall at lower latitudes. However, this inference must be weighed against the considerable uncertainty in future monsoon behavior that may stem from continued anthropogenic impacts such as aerosol loading and land-use change.

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