1. CONCEPT OF GLOBAL MONSOON

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Monsoon is one of defining features of Earth’s climate. This paper discusses an emerging concept, the global monsoon (GM), and demonstrates that the GM precipitation is a sensible measure of global climate variations in the last millennium. The GM is a response of the coupled atmosphere-land-ocean-creosphere-biosphere system to annual variation of solar radiative forcing. In the context of climatology, the GM can be quantitatively described by the sum of a solstitial mode and an equinoctial asymmetric mode. Global monsoon domain can be delineated by the annual range (local summer-minus-winter) of precipitation that exceeds 2 mm/day and 70% of the local annual mean rainfall. The year-to-year variability of the GM can be measured by GM precipitation (GMP) intensity, which represents the averaged annual range of precipitation in the GM domain. Using Global Precipitation Climatology Project (GPCP) data, we found that GMP has significantly increased in the past 29 years (1979-2007). By studying the millennial simulation with the ECHO-G model, we show that on the centennial-millennial timescale, the change of the GMP follows the effective radiative forcing better than the change of global mean surface air temperature, suggesting that the GMP is a valuable gauge for global climate change. Understanding the integrated property of the GM provides a linkage between paleomonsoon, modern monsoon, and future monsoon studies. Further research is required to better understand fundamental dynamics governing the GM system, as well as the linkage and differences among regional monsoons.

1. Introduction

The concept of monsoon has been evolving over time. The conventional definition of monsoon was solely based on annual reversal of prevailing surface winds (Ramage 1971). However, monsoon climate is also characterized by contrasting rainy summer and dry winter (Webster 1987; Webster et al. 1998). Seven regional monsoon systems associated with three continental pillars (Eurasia-Australia, Africa, and America) and adjacent oceans have been well recognized and documented: the South Asian monsoon (e.g., Webster et al. 1998), East Asian monsoon (e.g., Tao and Chen 1987), Australian monsoon (e.g., Davidson et al. 1983), northern African and Southern African monsoon (e.g., Hastenrath et al. 1995), Mexican and Southwest U.S. monsoon (e.g., Higgins et al. 1997), and South American monsoon (e.g., Zhou and Lau 1998).
All seven regional monsoons are driven and synchronized by the annual cycle of solar radiation, and they are bonded by the global divergent circulation. Therefore, the regional monsoons should not be studied in isolation. Trenberth et al. (2000) depicted global aspect of the monsoon system as a global-scale persistent overturning of the atmosphere, throughout the tropics, that varies with season. Considering the physical principle of conservation of mass, moisture, and energy as it applies to the global atmosphere and its exchange of energy with the underlying surfaces, analysis of overall monsoon variability and changes from a global perspective is imperative and advantageous for understanding fundamental monsoon dynamics.

In this paper, we will emphasize global monsoon precipitation (GMP hereafter) because in theory the variation of the global atmospheric overturning (divergent) circulation is intimately associated with the seasonal variation of monsoonal precipitation. Furthermore, the GMP is one of the essential measures of global water and energy cycle, and plays an important role in organization of regional monsoon variations. The GMP may be critical to paleoclimate variation as precipitation heating holds a key in linking external radiative forcing and the atmospheric general circulation.

The global monsoon (GM) is an emerging concept. Whether this is an adequate terminology remains to be illuminated. In this study we discuss aspects of this emerging concept. The goal of the study is to stimulate further studies for improving our understanding of the fundamental dynamics that determines variability and change in the GM precipitation.

2. What is the Essence of the Global Monsoon?

Global monsoon manifests itself as a response of the coupled atmosphere-land-ocean-cryosphere-biosphere system to annual variation of solar radiative forcing. In the context of climatology, GM can be quantitatively defined by the first two principal empirical orthogonal modes of the annual variation of global precipitation and low-level (850 hPa) winds (Wang and Ding 2008). Both modes have an annual period (Fig. 1a). The first mode, which accounts for 71% of the total annual variance, features an interhemispheric contrast in precipitation (Fig. 1b) and can be simply described as June-July-August-September (JJAS) minus December-January-February-March (DJFM) precipitation pattern (Fig. 1d). Thus, the first mode is called solstitial mode, which reflects the impact of antisymmetric annual solar forcing with a one-to-two-month phase delay in the atmospheric response. The second mode has also an annual period with the maximum and minimum occurring around April and October, respectively. Its spatial pattern (Fig. 1c) resembles the April-May (AM) minus October-November (ON) precipitation and circulation pattern (Fig. 1e). Therefore, the second mode represents an equinoctial asymmetric mode, or the spring-fall asymmetry, which is one of the important features of the seasonal variation in the tropical and monsoon circulation. Only the third mode depicts semiannual variation, reflecting the effect of solar forcing that crosses the equator twice a year and the temporal asymmetry in monsoon strength and duration between JJAS and DJFM (Wang 1994). As shown in Fig. 1, the primary features of the annual cycle of tropical precipitation and low-level circulation can be represented by combination of the
solstitial mode and equinoctial asymmetric mode; together, they account for 84% of the annual variance and they can be used to quantitatively define the GM.

![Figure 1](image.png)

Figure 1. (a) Normalized principal components of the first two multi-variable EOF modes and their corresponding spatial patterns of precipitation (shading, unit: mm/day) and winds (vectors in units of m/s) at 850 hPa for (b) EOF1 and (c) EOF2, respectively. (d) The differential precipitation rate (mm/day) and the 850 hPa winds between June through September and December through March (namely, JJAS minus DJFM). (e) April-May mean minus the October-November mean precipitation rate (mm/day) and the 850 hPa winds. Winds with wind speed less than 1 m/s are omitted in (b) and (c). Winds with wind speed less than 4 m/s and 2 m/s are omitted in (d) and (e), respectively. (adopted from Wang and Ding 2008)

3. How to Define the Global Monsoon Domain?

Wang (1994) attempted to delineate monsoon climate regime over the global tropics using outgoing longwave radiation (OLR) data. Using satellite observed rainfall, Wang and Ding (2006) proposed a way to identify monsoon precipitation domain on globe. The delineation was based on the fact that the contrast between rainy summer and dry winter is an essential characteristic of the monsoon climate (Webster 1987). Thus, the annual range (AR) that depicts the differences between local summer and winter precipitation is a fundamental parameter to
depict monsoon precipitation. More specifically, AR can be defined by the local summer-minus-winter precipitation, i.e., JJA minus DJF precipitation in the northern hemisphere (NH) and DJF minus JJA in the southern hemisphere (SH).

Figure 2 presents spatial distribution of the ratio of the AR over the annual mean precipitation. Note that the negative value (the light gray area in Fig. 2) implies a Mediterranean regime, which features a wet winter and a dry summer. All continental monsoon regions have large AR of precipitation in comparison with the annual mean.

![Normalized annual range of precipitation and GMP domain](image)

Figure 2. Annual range of precipitation normalized by annual mean precipitation (gray shading) and the monsoon precipitation domain outlined by the black curves. The monsoon precipitation domain is defined by the annual range greater than 2 mm/day and 70% of the annual mean precipitation. The data used are GPCP precipitation measurements. (modified from Wang and Ding 2006)

Since a typical monsoon climate is characterized by not only a significant AR but also a concentration of rainfall in the local summer, the monsoon domain can be defined by the regions in which the AR (JJA and DJF difference) exceeds 2 mm/day and accounts for more than 70% of the annual mean. The first criterion distinguishes the monsoon climate from arid and semi-arid or Mediterranean climate regimes. The second criterion warrants a monsoon-like seasonal distribution of rainfall: concentration of precipitation during local summer, so that it distinguishes the monsoon climate from equatorial perennial rainfall regime where the AR is moderate compared to its annual mean.

The major monsoon precipitation regions that are defined by the AR (JJA and DJF difference) exceeding 2 mm/day and 70% of the annual mean are shown by the thick lines in Fig. 2. The GMP domain includes six major continental monsoon regions: South and East Asia, Indonesia-Australia, Northern Africa, Southern Africa, North America, and South America. Note that most regional monsoon regions embrace an adjacent oceanic region. Thus, oceanic monsoon regions, including the South Asian and East Asian marginal seas, the Philippine Sea, the southwest Indian Ocean, and the eastern North Pacific off coast of Mexico are extensions of the corresponding continental monsoons and have a typical monsoon precipitation characters;
thereby they are integral parts of the corresponding regional monsoon systems. In the subtropical mid-South Pacific, however, there is a pure oceanic region that has similar seasonal distribution as monsoon regimes. But, due to lack of the land-ocean thermal contrast, this oceanic region is not a typical monsoon region. Based on the above defined monsoon domain, a concise and objective definition of rainy season characteristics is proposed for worldwide monsoon regions (Zhang and Wang 2008).

It should be noted that studies have been conducted to test the sensitivity of the monsoon domain to the two criteria proposed here. We found that the global monsoon domain is not very sensitive to the two criteria used here. In the previous study, Wang and Ding (2006) used an alternative second criterion: the local summer (JJA or DJF) precipitation is greater than 35% of the annual total. The results derived from this alternative criterion are very similar to that shown in Fig. 2. Liu et al. (2009) defined the local summer as May through September (MJJAS) in NH and November through March (NDJFM) for SH. The global monsoon precipitation domain was defined by the region in which the AR (MJJAS and NDJFM difference) of precipitation exceeds 2 mm/day and the local summer precipitation exceeds 55% of annual rainfall. The resultant domain was also in a general agreement with that shown in Fig. 2.

4. How to Measure Global Monsoon Precipitation Intensity?

The strength of the GMP varies on variety of time scales ranging from interannual to geological. How do we measure intensity change of the GMP and its regional components? As we elaborated before, the simplest measures of monsoon precipitation intensity at a given place is the AR. The larger the AR is, the larger the contrast between wet summer and dry winter, thus the stronger the monsoon is. Note also that the AR is normally dominated by local summer rainfall; therefore, to a large extent the local summer precipitation can also provide a meaningful measure (Wang and Ding 2006). For simplicity, we will use the AR measure in the present study.

With this in mind, the monsoon intensity in a given regional domain or in the GM domain, can simply be computed by area average of the AR at each grid within the given domains. The averaged AR over the GM domain may be termed as the GMP intensity. In a similar way, we can define intensities for the NH monsoon precipitation (NHMP) and SH monsoon precipitation (SHMP), and various regional monsoon precipitation intensities. Since the monsoon domain may change over time or from model to model, to facilitate comparison, we will use the observed monsoon domain in the present day climate as a reference region to compute the area average AR. Also, in computing the yearly varying AR, we specify the difference between the local summer and the following winter as the AR of the year when summer monsoon occurs.

A complemented approach is to reveal the coherent pattern of the year-to-year variation (or changes) in the AR. To this end, the leading Empirical Orthogonal Function (EOF) pattern of the AR can be used to describe the primary spatial variability, while the corresponding principal component can be used to describe its temporal variation. The two methods are complementary and better be jointly used. An example will be given in the next section.
5. The Present-day Variation of the Global Monsoon Precipitation Intensity

Wang and Ding (2006) constructed time series of monsoon precipitation intensity averaged over the land regions of the global, the NHMP and SHMP domains using four different sets of land-based rain gauge data from 1948 to 2003. The time series of the ensemble mean of the four datasets indicates a decreasing trend in the global land monsoon precipitation, primarily owing to reduced NH summer monsoon rainfall from the 1960s to 1970s, especially over West

![Figure 3](image_url)

Figure 3. (a) The GPCP global monsoon precipitation (GMP) intensity from 1979 to 2007. Shown are also its land and oceanic components. (b) The spatial pattern of the second EOF mode of the normalized annual range (AR) anomalies over the global monsoon regions derived for 1979-2007 using GPCP. The bold contour indicates the boundaries of the monsoon domain. (c) Statistical significance of the long term trends in AR at each grid point by Mann-Kendall rank statistics.
Africa. However, after 1980 the global land monsoon rainfall has no significant trend. This weakening tendency has been reproduced using an Atmospheric General Circulation Model (AGCM) driven by observed sea surface temperature (SST) (Zhou et al. 2008).

In the last three decades (1979-2007), satellite observations provide global coverage for estimated precipitation, making it possible to investigate the variability of the GMP intensify variability. Here we used Global Precipitation Climatology Project (GPCP) dataset (Huffman et al. 1997) which provides global precipitation measurements over the last 29 years, charted on a 2.5 by 2.5 degree grid. The climatological mean globally averaged precipitation rate is 2.61 mm/day, with a tiny yearly standard deviation of 0.03 mm/day; no trend was seen for the total global precipitation (Allen and Ingram 2002). What about the GMP, particularly over the oceanic monsoon region? To answer this question, we divided the GM domain into land and ocean portions.

Figure 3a shows that the GMP intensity has an increasing trend from 4.6 mm/day to 5 mm/day, significant at the 95% confidence level, mainly due to the trend in the oceanic monsoon regions and no significant trend was detected for the global land monsoon intensity. During the period of 1979 to 2005, the trend of the global mean temperature was estimated about 0.17°C per decade (Brohan et al. 2006; Smith and Reynolds 2005; IPCC AR4). The rising trend in GMP intensity for the same period is about 9%. However, the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) data (Xie and Arkin 1997) do not show an evident increasing trend.

Figure 3b shows the spatial pattern of the monsoon intensity trend derived by the second EOF mode of the GPCP AR of precipitation. The corresponding principal component has a correlation coefficient of 0.80 with the GMP intensity. To test the significance of the long term trend for the time series of AR at each grid, we used nonparametric Mann-Kendall rank statistics (Kendall 1955) and the results are shown in Fig. 3c. Combining the results from Fig. 3b and 3c, we see that the significant increasing trend of monsoon intensity in the past 29 years are found over the Bay of Bengal, western Arabian Sea, southern China, Venezuela, South America, and Northern Africa. Significant decreasing trend is found near the equatorial Southern Africa.

### 6. Centennial-Millennial Variation of the GMP Simulated by ECHO-G Model

Is the GMP a useful concept for examining response of Earth climate to external forcing? To address this question, Liu et al. (2009) have examined the centennial-millennia I variability of the GMP simulated by the ECHO-G model, a global coupled atmosphere-ocean climate model (Legutke and Voss 1999), to understand how the GM evolves as a whole under the present condition and on the centennial-millennial time scale. The millennial integrations include a free run, which was generated using fixed external (annually cycling) forcing that is set to the present-day values (Zorita et al. 2003), and a forced run that was forced by three external forcing factors: solar variability, the effective radiative effects from stratospheric volcanic aerosols, and greenhouse gas concentrations in the atmosphere including CO₂ and CH₄ for the period from 1000 to 1990 AD (Gonzalez-Rouco et al. 2003; von Storch et al. 2004; Zorita et al.
Bin Wang et al.

2005). The simulated annual mean precipitation and solstice mode in ECHO-G simulation is comparable to those assimilated data in reanalyses.

In the control (free) run, there is no trend and no significant centennial variation in the NHMP, SHMP, and GMP. Further the NHMP and SHMP are not related, which indicates that the monsoon intensities between the two hemispheres are independent of each other in the absence of coordination of the external forcing. In the forced run, on the other hand, the NHMP and SHMP are significantly correlated on multi-decadal to centennial time scales and notable centennial-millennial variations can be seen in the GMP (Fig. 4). Strong GMP intensity is observed around 1030-1240, which is viewed as the model counterpart of the Medieval Warm Period (MWP). Weak GMP is observed during the Little Ice Age (LIA) from 1450-1850 with three minima occurring, respectively, around 1460, 1685, and 1800 (Liu et al. 2009). These three rainfall minima fell in the Spörer Minimum (1420-1570), the Maunder Minimum (1645-1715), and the Dalton Minimum (1790-1820) periods of low sunspot activity and in the two latter cases increased volcanic activity, as well (Soon and Yasukochi 2003; Haltia-Hovi et al. 2007). This suggests a connection with the centennial-scale modulation of the solar and/or volcanic radiative forcings.

What causes the millennial-centennial variations? Figure 4 shows that the GMP intensity tends to vary in phase with the effective radiative shortwave forcing, especially on the millennium time scales (Fig. 4a and 4d). The millennial variation of the GM precipitation in this model (peaks in MWP and present and dips in LIA eras) can be well explained by changes in the direct solar irradiance. The three GMP minima during the LIA concur with the three minima in shortwave forcing, which further supports the impact of the effective solar forcing on the GM precipitation.

Why does the GMP respond to effective solar forcing sensitively? Liu et al. (2009) explained that when effective radiative flux increases during the local summer, the magnitude of land warming is much stronger than that in the adjacent ocean, thus the thermal contrast between continent and ocean gets reinforced (Fig. 4e). This thermal contrast further enhances the pressure differences between land monsoon regions and the surrounding oceans (Fig. 4f) and thus strengthens the monsoon circulation in the presence of Coriolis force and associated rainfall.

It is of interest to observe that the GMP intensity has a closer correlation with the effective radiative forcing than the global mean temperature (Fig. 4c, d) as the correlation coefficient between the GMP and effective solar radiation is 0.78, while that global mean temperature with effective solar radiation is 0.69. Thus, the response to varying external forcing of the GMP is more sensitive than global mean temperature, especially the centennial variation. How can this happen? Figure 4 indicates that the global land-ocean temperature difference is better correlated with the effective radiative forcing than the global mean temperature does. This is because the warming is primarily occurring over the land (not the ocean) and the land area is only 30% of the globe. When effective solar forcing enhances, the land-sea contrast increases could be more significant than the global mean temperature. Since the GMP intensity is driven by the land-ocean thermal contrast, the GMP intensity should be more sensitively respond to the external forcing.
Figure 4. The 31-year running mean time series from 1000 to 1990 AD of (a) the effective solar radiation (W/m²), (b) CO₂ concentration (ppm), (c) global mean temperature (K), (d) global monsoon precipitation (GMP) intensity (mm/day), (e) global land-ocean temperature difference (K), (f) global land-ocean sea-level pressure difference (hPa), and (g) inter-hemispheric temperature difference (K). The numbers shown in the lower-right corners indicate the correlation coefficients of the effective radiation forcing with the five global response factors (c, d, e, f, g). The inter-hemispheric temperature difference is defined by the NH averaged temperature minus the SH averaged temperature. (modified from Liu et al. 2009)
7. Concluding Remarks

In this paper, we discussed aspects of an emerging concept, the Global Monsoon (GM). We show that the intensity of GMP provides a useful parameter to quantify the change in annual cycle of the Earth climate. This new measure is complimentary to the global mean temperature which measures change in the annual mean climate. The GMP also provides important information about change in the global precipitation, which is a variable that is far more relevant for food production and water supply than temperature change. Using millennial simulation with ECHO-G model, we found on the centennial timescale, the change of the GM strength follows the effective radiative forcing better than the changes of the global mean surface temperature. We concluded that GMP is a valuable index for measuring the global climate change.

The GMP intensity is an effective measure of the forced response of the global tropical circulation. Therefore on orbital and suborbital scale, GMP can provide a meaningful measurement of the coordinated regional monsoon variations. On interannual and interdecadal time scales when internal feedback processes play dominant roles, one would of course concern with regional variations, but GMP remains useful for detecting global signals that may driven by major modes of variability, such as El Niño-Southern Oscillation (ENSO). GMP may provide an opportunity for revealing such aspects of global variability. In the continuing increases of green house gases, one would also concern with change of the annual cycle and GMP may provide such a measure for detection of it.

Further research is required to better understand fundamental dynamics governing the variability of the GM system on various time scales and the linkage and differences among regional monsoons. Strategy used in this study provides a linkage between paleo-monsoon, modern monsoon, and future monsoon studies. It will pave a new ground and develop a new interdisciplinary approach for studying monsoon dynamics.

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