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Trends in global monsoon area and precipitation over the past 30 years

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[1] The analysis of the GPCP and CMAP datasets during the past 30 years (1979–2008) indicates that there are consistent increasing trends in both the global monsoon area (GMA) and the global monsoon total precipitation (GMP). This positive monsoon rainfall trend differs from previous studies that assumed a fixed global monsoon domain. Due to the increasing trends in both the GMA and GMP, a global monsoon intensity (GMI) index, which measures the global monsoon precipitation amount per unit area, is introduced. The GMI measures the strength of the global monsoon. Our calculations with both the GPCP and CMAP datasets show a consistent downward trend in the GMI over the past 30 years. This decreasing trend is primarily attributed to a greater percentage increase in the GMA than in the GMP. A further diagnosis reveals that the decrease of the GMI is primarily attributed to the land monsoon in the GPCP, but to the oceanic monsoon in the CMAP. **Citation:** Hsu, P.-C., T. Li, and B. Wang (2011), Trends in global monsoon area and precipitation over the past 30 years, *Geophys. Res. Lett.*, *38*, L08701, doi:10.1029/2011GL046893.

1. Introduction

[2] Monsoon precipitation accounts for a great portion of annual global rainfall. More than two-thirds of the world's populations live in monsoon regions. The changes to this monsoon precipitation under global warming may impose a great social and economic impact on billions of people living in monsoon regions. Using the Global Precipitation Climatology Project (GPCP) data during 1979–2003, *Wang and Ding* [2006] defined a global monsoon index and found that there is an increasing trend in global monsoon rainfall during the past 25-yr period. With the same analysis method, *Zhou et al.* [2008a] used three datasets, i.e., the GPCP, the CPC Merged Analysis of Precipitation (CMAP) and the Special Sensor Microwave Imager (SSM/I), to detect the oceanic monsoon rainfall changes during 1979–2000. They found that the GPCP and SSM/I reveal robust increasing trends, while the CMAP indicates a weak decreasing trend.

[3] It is worth mentioning that in both the studies above, the total monsoon rainfall is calculated based on a fixed global monsoon domain derived from long-term (either 25-year or 22-year) climatology. As we know, global circulation and ocean and land surface temperature experience a marked interannual variation [*Yang and Lau*, 2006]. It is likely that associated with this circulation/surface temperature change, the global monsoon area (GMA) [*Wang and Ding*, 2006] may be also subject to a large year-to-year variation. Thus it would be reasonable to consider such a change when calculating the global monsoon total precipitation (GMP) trend. Motivated by the aforementioned studies, we intend to re-calculate the GMP and its trend according to a varying GMA with the use of both the GPCP and CMAP data for a 30-year period (1979–2008).

2. Definition of the Global Monsoon Area

[4] Two sets of monthly precipitation data derived from the GPCP [*Adler et al.*, 2003] and CMAP [*Xie and Arkin*, 1997] are used to investigate the possible trends in the GMA and GMP over the past 30 years (1979–2008). The horizontal resolution of both the GPCP and CMAP datasets is 2.5 degree latitude by 2.5 degree longitude. To more accurately define the monsoon area, the original datasets are interpolated into a 1 degree latitude/longitude grid using a bilinear interpolation technique.

[5] Following *Liu et al.* [2009], the GMA at each year is defined as the region in which the annual range of precipitation exceeds 2 mm day^{-1} and the local summer precipitation exceeds 55% of annual rainfall. Here the annual range is defined as local summer-minus-winter precipitation; in the Northern Hemisphere (NH) the summer is defined as May-September (MJJAS) and the winter is defined as November-March (NDJFM); in the Southern Hemisphere (SH) the definition is just opposite. The GMP is defined as summer (JJA for the NH and DJF for the SH) precipitation within the GMA.

[6] The definition of the GMA by *Liu et al.* [2009] is an improved version of *Wang and Ding* [2006]. The difference between the current GMA definition and that of *Wang and Ding* [2006] lies in the length of summer and winter months. *Wang and Ding* [2006] defined JJA for a northern summer and DJF for a northern winter. Regardless of the difference, the sign of the calculated GMP trends from both of the datasets remains the same. Because the GMA is defined based on the annual range of rainfall between the concurrent summer and the preceding winter, only 29-year data are used to define the GMA.

[7] Since the actual area in each grid box varies with latitude, we adopt an area-conserving metric when calculating the GMA and GMP. A linear regression analysis is applied to derive the slope of the GMA and GMP trends. The Mann-Kendall non-parametric statistical test [*Kendall*, 1955] is further used to identify the significance of the linear trends.

3. Results

[8] To illustrate how a varying GMA may affect the global monsoon total rainfall, we performed two calculations. In

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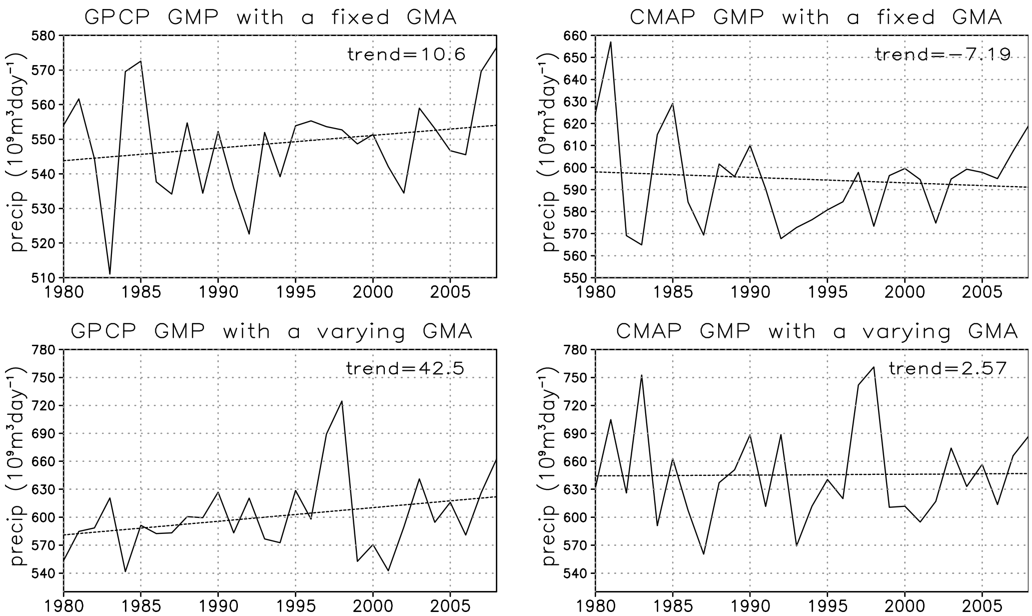

Figure 1. Time series of the global monsoon precipitation (GMP, unit:10^9 m^3 day^{-1}) calculated based on a (top) fixed and (bottom) varying global monsoon domain from the (left) GPCP and (right) CMAP datasets for the period of 1979–2008. The linear trend of each time series is presented by a dashed line, with a value of the linear trend [unit: 10^9 m^3 day^{-1} (29 yr)$^{-1}$] shown in each panel.

the first, the GMP was calculated based on time-independent GMA, derived from the 30-year climatological rainfall field. This strategy follows *Wang and Ding* [2006] and *Zhou et al.* [2008a]. In the second, the GMP was calculated based on an annually varying GMA. Figure 1 illustrates the time evolution of the GMP in both the fixed (Figure 1, top) and varying (Figure 1, bottom) GMA cases, based on the GPCP and CMAP data respectively. Consistent with *Wang and Ding* [2006] and *Zhou et al.* [2008a], the GMP shows an increasing trend with a slope of 10.6×10^9 m^3 day^{-1} (29 yr)$^{-1}$ in the GPCP data (Figure 1, top left), but shows a decreasing trend with a slope of -7.19×10^9 m^3 day^{-1} (29 yr)$^{-1}$ in the CMAP data (Figure 1, top right).

[9] As global land surface and ocean temperatures increased unevenly during past decades [*Intergovernmental Panel on Climate Change*, 2007], it is likely that the land-sea thermal contrast also changes with time. Because a monsoon system is largely attributed to the land-sea thermal contrast, the GMA might vary over the past 30 years. The GMA is now defined by the annual range of precipitation and the ratio of summer-to-annual rainfall for each monsoon year, as opposed to being defined by the climatologically averaged precipitation information. As shown in Figure 1 (bottom), when considering a varying GMA, there is a consistent increasing trend of the GMP in both the GPCP and CMAP, even though the slope in the GPCP [42.5×10^9 m^3 day^{-1} (29 yr)$^{-1}$] is much greater than 2.57×10^9 m^3 day^{-1} (29 yr)$^{-1}$ derived from the CMAP data. The application of the Mann-Kendall statistics indicates that those GMP trends are not significant at the 95% confidence level.

[10] The positive GMP trends in both the GPCP and CMAP, when considering a varying GMA, are attributed to the significant upward trends in the GMA in both the datasets. Figure 2 (top) shows that there is a steady increase in the GMA from 1979 through 2008, even with interannual fluctuation. For example, the Western Pacific Monsoon shows a significant eastward expansion, which contributes to an increased GMA in 1998. This change is related to anomalous convection and circulation over the tropical central-eastern Pacific associated with the 1997–1998 El Niño event. The slopes of the GMA trends from the GPCP and CMAP are 6.3×10^6 km^2 (29 yr)$^{-1}$ and 3.39×10^6 km^2 (29 yr)$^{-1}$, respectively. The trend in the GPCP is significant at 95% confidence level, while the trend in the CMAP is not statistically significant. A pair of dashed lines in Figure 2 (top) indicate 95% confidence intervals for the GMA trends. The expansion of the global monsoon area may contribute to a great portion of the total monsoon rainfall increasing trend, as a larger region would likely receive more rainfall. In order to verify that the increasing trend of GMA in the GPCP is robust rather than sensitive to the GMA definition and calculation metric, a sensitivity test is conducted by using different thresholds for the summer-to-annual rainfall ratio (Figure 2, bottom). Two calculation metrics are applied to the GMA computation. The first metric uses an area-conserving method (Figure 2, bottom left). The second metric simply counts the number of grids (Figure 2, bottom right). The GMA shows significant positive trends under most thresholds. It is noted that the positive trends in GMA based on the second metric are more significant. The sensitivity test results indicate that the signal of the GMA in the GPCP during the past 30 years is robust.

[11] Figure 2 (middle top) further illustrates where the GMA has expanded in the past 30 years. It shows simply the difference of the GMA averaged between a later period (1994–2008) and an earlier period (1979–1993). Consistent with the upward GMA trends, the GMA differences between these two periods are 9×10^5 km^2 and 1.1×10^5 km^2 in the GPCP and CMAP, respectively. The spatial distributions of the GMA changes are quite similar in the GPCP and CMAP. In general, the increase in the monsoon regions (represented by the blue shaded areas) occurs in

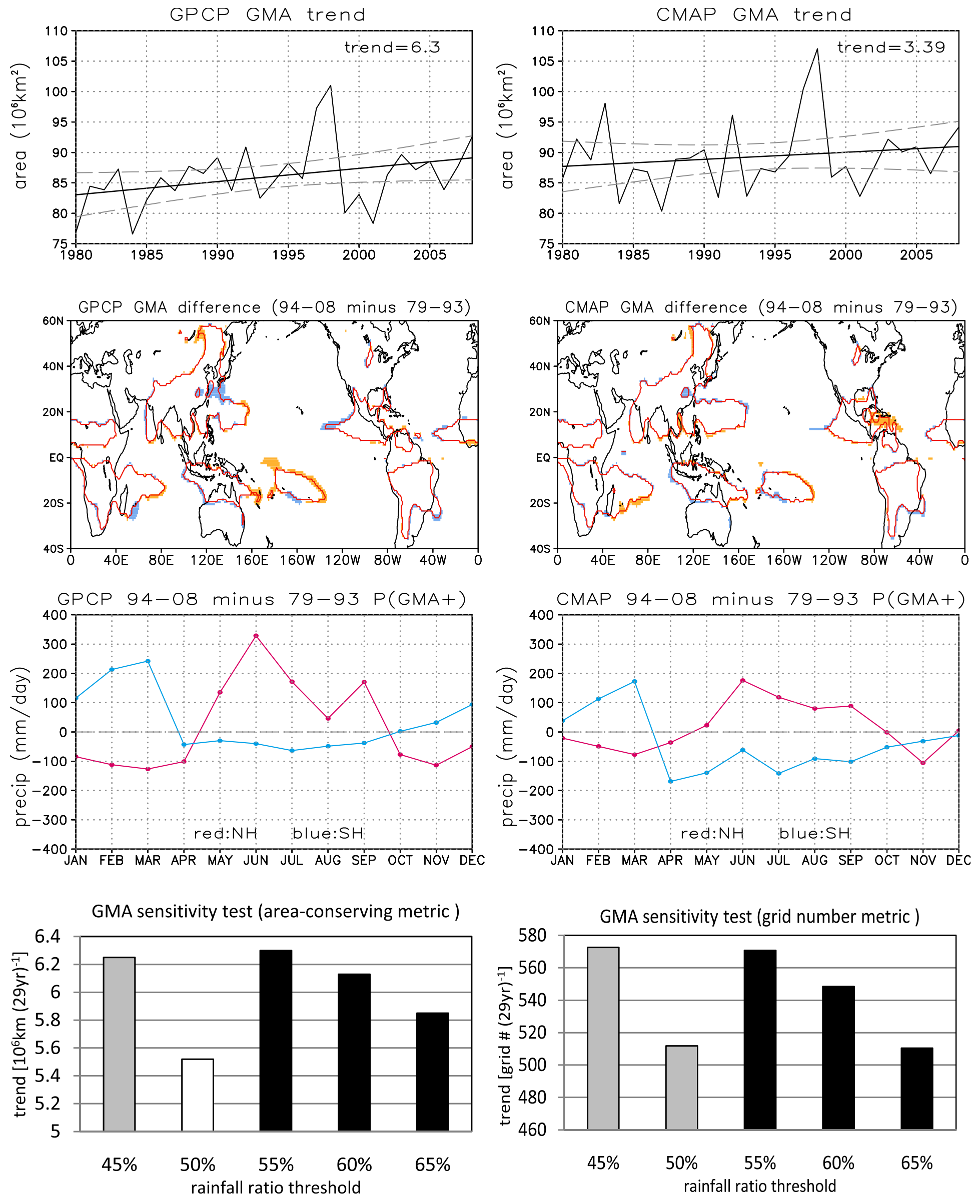

Figure 2. (top) Time series of the global monsoon area (GMA, unit:10^6 km^2) calculated based on the (left) GPCP and (right) CMAP datasets for the period of 1979–2008. The linear trend of each time series is presented by a thick black line, with a value of the linear trend [unit: 10^6 km^2 (29 yr)$^{-1}$] shown in each panel. Dashed lines indicate 95% confidence intervals for the GMA trends. (middle top) The difference of the GMA between 1994–2008 and 1979–1993. Blue (orange) shading indicates the positive (negative) GMA anomaly. Red contours denote the climatological GMA calculated based on averaged precipitation during 1979–2008. (middle bottom) The difference of seasonal precipitation distribution between 1994–2008 and 1979–1993 over expanding GMA regions in the Northern (red line) and Southern (blue line) hemisphere respectively. (bottom) GMA changes using different thresholds of summer-to-annual rainfall ratios in the GPCP. GMA calculations based on both the area-conserving [10^6 km^2 (29 yr)$^{-1}$] and unit grid metrics [$1° \times 1°$ grid # (29 yr)$^{-1}$] are shown in Figures 2 (bottom left) and 2 (bottom right), respectively. Trends exceeding 95% (90%) confidence level are indicated by black (gray) bars.

the poleward edges of the tropical monsoon region near 15°–30° north and south. We further examine the changes in the seasonal distribution of precipitation in those expanded GMA regions (the blue shaded areas), shown in Figure 2 (middle bottom). In the expanding GMA regions, the precipitation characteristics tend to be more monsoon-like with an enhancing (decreasing) rainfall during summer (winter) in both hemispheres. The poleward expansions of GMA might be attributed to the widening of tropical circulations associated with significant poleward expansion of the Hadley cell during the summers from 1979 to 2005 [*Fu et al.*, 2006].

[12] Considering the changes in both the GMA and GMP, we introduce the global monsoon intensity (GMI) index. This index is defined as the global monsoon precipitation amount per unit area, similar to *Zhou et al.* [2008b], and this can be used to measure the changes in the global monsoon strength. Figure 3 (top) shows the time series of the GMI based on the GPCP and CMAP data over the past 30 years.

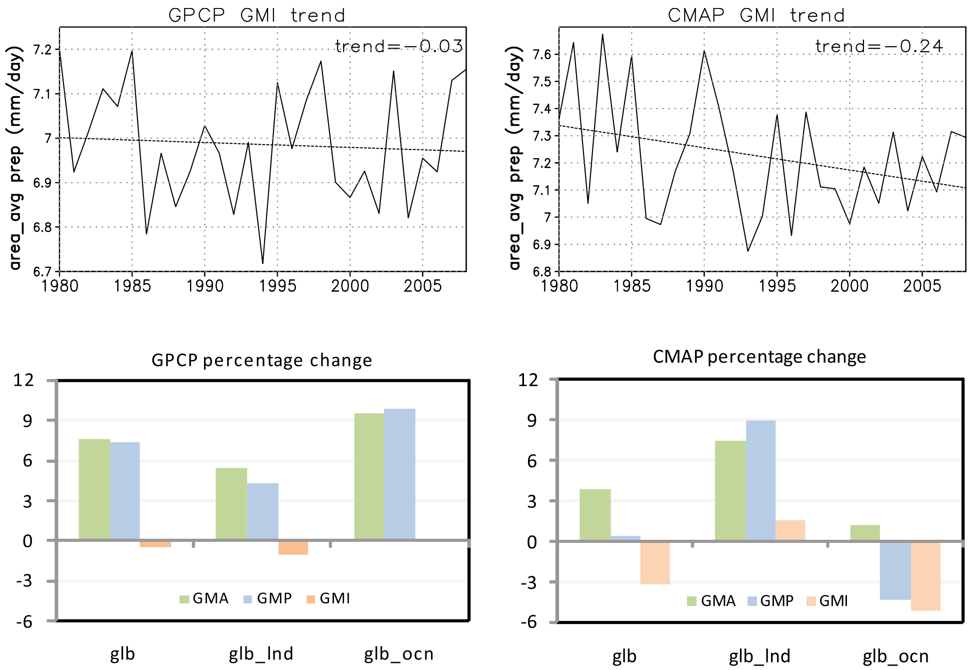

Figure 3. (top) Time series of the global monsoon intensity (GMI, unit: mm day $^{-1}$) calculated based on the (left) GPCP and (right) CMAP datasets for the period of 1979–2008. The linear trend of each time series is presented by a dashed line, with a value of the linear trend [unit: mm day $^{-1}$] shown in each panel. (bottom) Percentage changes (unit: %) of the GMA (green), GMP (blue) and GMI (orange) calculated from the (left) GPCP and (right) CMAP datasets in the global monsoon domain (denoted by "glb"), the global land monsoon region ("glb_lnd"), and the global oceanic monsoon region ("glb_ocn").

Interestingly, *they both display a weakening trend*, suggesting that the monsoon intensity is actually weakening over the past 30 years. The linear slope of the decreasing trend in the GPCP (CMAP) is −0.03 (−0.24) mm day^{-1} (29 year)$^{-1}$, both of which are relatively weak and don't exceed the 95% significance level. The downward trend in the GMI implies that although the GMA and GMP both increase with time, the growth rate in the former is larger than that in the latter.

[13] The analysis above indicates that both the GPCP and CMAP datasets show a positive trend in the GMA and GMP and a negative trend in the GMI during the past 30 years. What is the relative contribution of the land and ocean to the aforementioned trends? Figure 3 (bottom) shows the relative contributions of the land and oceanic monsoons to the percentage change of the GMA, GMP and GMI. Here the percentage change is defined as a ratio between the linear trend difference between 2008 and 1980 and the 29-yr mean value. Note that a large portion of the GMA percentage increase is contributed to the land monsoon in the CMAP. This differs from the GPCP, in which a dominant percentage contribution comes from the oceanic monsoon. Nevertheless, both the datasets show an increase in the land and oceanic monsoon areas. Regarding the GMP, while both the land and oceanic monsoons contribute to an increase in the total precipitation (with the latter being greater than the former) in the GPCP, an opposite sign of the percentage change appears in the CMAP, where the land monsoon contribution prevails. The difference in the percentage changes of the GMA and GMP determines the sign of the GMI. The GMI change becomes negative when the GMA change is positive and the GMP change is negative, or, when both are positive but the percentage change of the GMA is greater. Figure 3 (bottom) illustrates that the GMI change depends primarily on the contribution from the land monsoon in the GPCP but from the oceanic monsoon in the CMAP.

4. Summary and Discussion

[14] In this study, by considering a varying global monsoon domain, we obtained a consistently increasing trend in the global monsoon total precipitation over the past 30 years from both the GPCP and CMAP data, which is different from the previous findings of *Wang and Ding* [2006] and *Zhou et al.* [2008a] through use of a fixed global monsoon domain. Our results suggest that in the past 30 years with an increase in the global mean surface temperature, the global monsoon total precipitation is strengthened.

[15] It is further found, based on both the GPCP and CMAP datasets, that the global monsoon area exhibits an increasing trend over the past 30 years. The upward GMA trend is robust in the GPCP, even when using different precipitation thresholds and area statistical metrics, while it is relatively small and not statistically significant at 95% confidence level in the CMAP. The expansion of the monsoon regions occurs primarily at the poleward edges of tropical monsoon regions at 20°–30° north and south. People living in those regions might therefore be expected to experience a more monsoon-like climate pattern, replete with a wetter summer and a drier winter under global warming. The increase in the global monsoon domain contributes to a significant portion of the total monsoon precipitation increase in both the GPCP and CMAP datasets.

[16] To quantify the change in strength of the global monsoon, a global monsoon intensity (GMI) index is introduced. It is defined as the global monsoon precipitation amount per unit area. Our result shows a downward trend in the GMI from both the GPCP and CMAP datasets, suggesting that the global monsoon strength is decreasing. A further analysis shows that the decrease in the GMI is primarily attributed to the change in the land monsoon in the GPCP, but in the CMAP is attributed to the change in the oceanic monsoon.

[17] The changes in land and oceanic GMI show opposite signs between the GPCP and CMAP. According to previous studies [*Wang and Ding*, 2006; *Zhou et al.*, 2008b], the trends in the land monsoon rainfall derived from the GPCP are consistent with rain-gauge data. Over the ocean, different algorithms were used in the GPCP and CMAP rainfall retrieval. Compared to an independent data source, SSM/I, the trend in the oceanic monsoon rainfall derived from the GPCP has the same sign while the trend derived from the CMAP has an opposite sign [*Zhou et al.*, 2008a]. The arguments above suggest that the results obtained in this study based on the GPCP precipitation data are probably more reliable than those derived from the CMAP.

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