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Advanced Asian summer monsoon onset in recent decades

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[1] In this paper, we first elucidate the significant seasonality in long-term trends in the Asian monsoon on a monthly mean basis. Advanced monsoon onsets over the Bay of Bengal and the western Pacific were evident in recent decades. Increasing rainfall in May along 10°N reflected the advanced monsoon onset. Decreasing rainfall trends in June along 10°N were also detected. Because the rainfall trends in July and August showed less significance, the monsoon transition phase should be discussed in the context of climate change rather than boreal summer mean field. The advanced monsoon onset and weakening of the monsoon during early summer are most likely to be attributed to the heat contrast between the Asian landmass and the tropical Indian Ocean. The heating trend over the Asian landmass primarily contributes to the heat contrast variability with the persistent SST increase in the Indian Ocean throughout the season.
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1. Introduction

[2] The long-term variability of the Asian monsoon under increases in greenhouse gases and anthropogenic aerosols has been a vital issue in recent decades because of the region's high population. Many studies have revealed long-term change in the Asian summer monsoon rainfall, especially over China [*Ding et al.*, 2008; *Yu and Zhou*, 2007; *Zhao et al.*, 2010]. It has been suggested that the trends in monsoon rainfall in China and India were due to increases in black carbon and sulphate aerosol [*Menon*, 2002; *Ramanathan et al.*, 2001]. Most previous studies have focused and assessed on the boreal summer mean field (e.g., averaging from June to September). However, the Asian monsoon climate is characterized by strong seasonal variations with dry and rainy seasons. The seasonal march of the Asian summer monsoon displays a stepwise northward and northeastward migration of rainfall, with abrupt onset during boreal spring and summer [*Tao and Chen*, 1987; *Wu and Wang*, 2001]. Because of the large seasonal variability, the long-term trend of the Asian monsoon should exhibit seasonally dependent features that must be taken into consideration. Here, we analyze the trends of the Asian monsoon rainfall and water vapor flux during 1979–2008 on a monthly mean basis to clarify the seasonality of the Asian monsoon trend. We focus on the transition phase from boreal spring to summer and elucidate the nature of the advanced monsoon onset in recent decades.

[3] We mainly used the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) [*Xie and Arkin*, 1997], wind circulation, temperature and humidity data from the National Centers for Environmental Prediction (NCEP) DOE reanalysis II data [*Kanamitsu et al.*, 2002], and the Hadley Center sea surface temperature (SST) dataset [*Rayner et al.*, 2003] for the period 1979–2008, chosen for satellite data availability. The non-parametric Mann-Kendall test was applied for assessment of the trends.

2. Seasonality of Asian Monsoon Long-Term Trend

[4] We calculated the long-term trends of the Asian summer monsoon rainfall and water vapor flux during 1979–2008 on a monthly mean basis. Significant rainfall trends over the Asian monsoon area occur in May and June. In May, an increasing rainfall trend over the Arabian Sea, Bay of Bengal, South China Sea, and western Pacific was detected (Figure 1a). A 4–6 mm/day increase in the past 30 years accounts for about 50% of the climatology. A decreasing rainfall trend over the southern Indian Ocean was also found. In contrast, rainfall over the areas where an increasing trend was seen in May had a significant decreasing trend in June (Figure 1b). The increasing rainfall trend over southern China was also remarkable in June. These rainfall trends were consistent with the monsoon circulation and water vapor flux trends in the lower troposphere, especially westerly wind anomalies accelerated along the 10°N line in May and strong anti-cyclonic circulation anomaly over the western Pacific in June. Interestingly, rainfall and water vapor flux trends in May were similar to seasonal evolution from May to June (Figure 1c). This means that the rainfall and circulation pattern in May during recent decades is becoming closer to that in June during previous decades, suggesting that the Asian summer monsoon has started earlier in recent decades. On the other hand, the rainfall trends in June were quite similar to that in boreal summer mean (June-September; JJAS), but the amplitude was more than twice (Figure 1d). This implies the large contribution of rainfall long-term variability in June to that in boreal summer (JJAS) mean. Incidentally the rainfall trends in seasonal mean between May and September showed less significance along the 10–15°N (figure not shown). Above rainfall trends are also robust in other rainfall data sets (Figure S1 in the auxiliary material).[1]

[5] Figure 2 shows a Hovmöller diagram of rainfall trends along 10–15°N, climatologically peak area of monsoonal rainfall, superimposed with the climatology. Increasing rainfall trends in May and decreasing rainfall trends in June are prominent. However, the Asian monsoonal rainfall in

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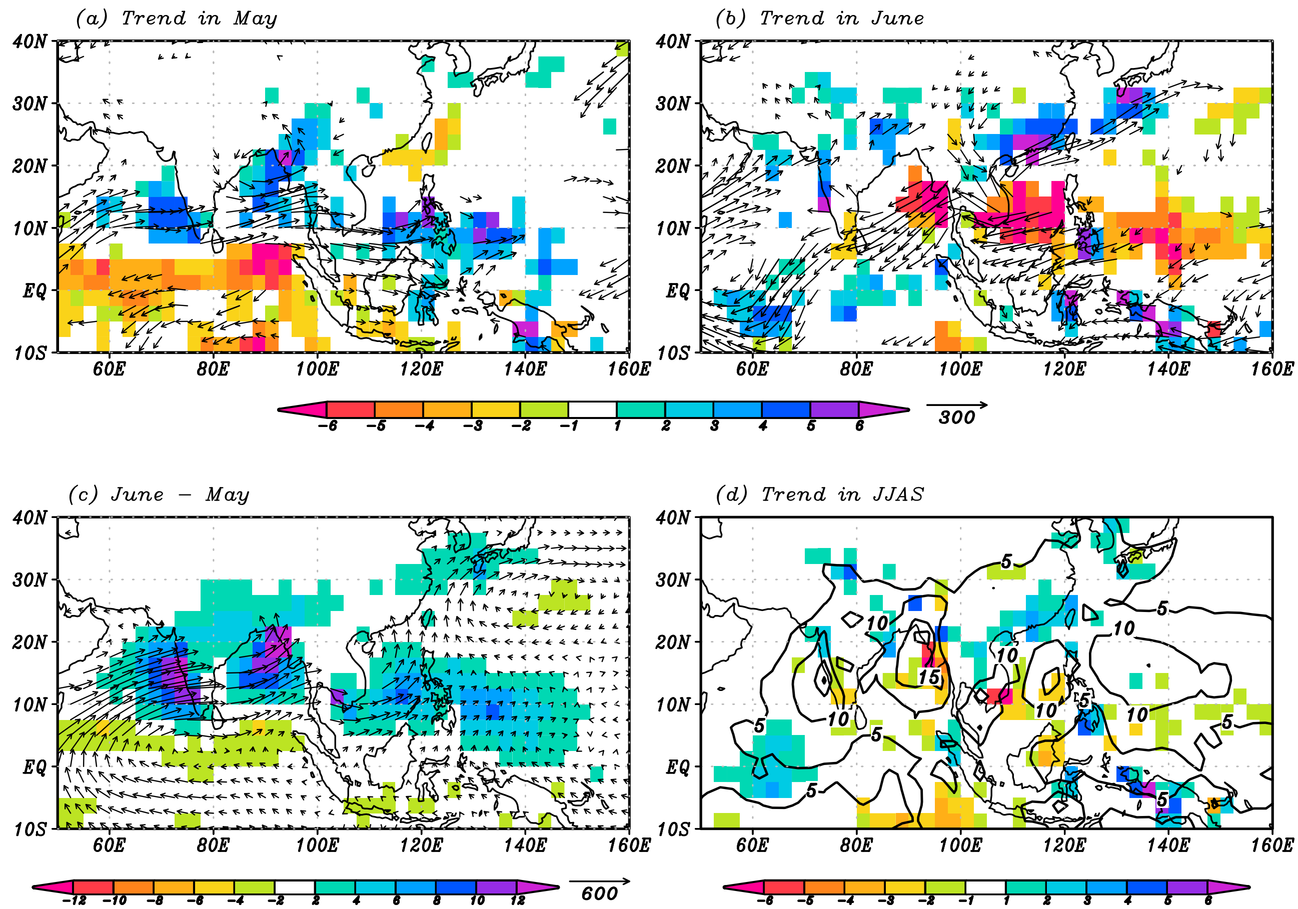

Figure 1. (a) Linear trends of rainfall (CMAP: Shading: mm/day) and vertical integrated water vapor flux (NCEP DOE reanalysis II: vector: kg m^{-1} s^{-1}) in May. All values were multiplied by 30 (years) for the period 1979–2008. Only those that are significant at the 95% level following the Mann-Kendall test are plotted. (b) Same as Figure 1a but for June. (c) Climatological difference in rainfall and vertical integrated water vapor flux between June and May. (d) Linear trend of rainfall in boreal summer (June-September) mean. Contour denotes climatological summer mean rainfall (mm/day).

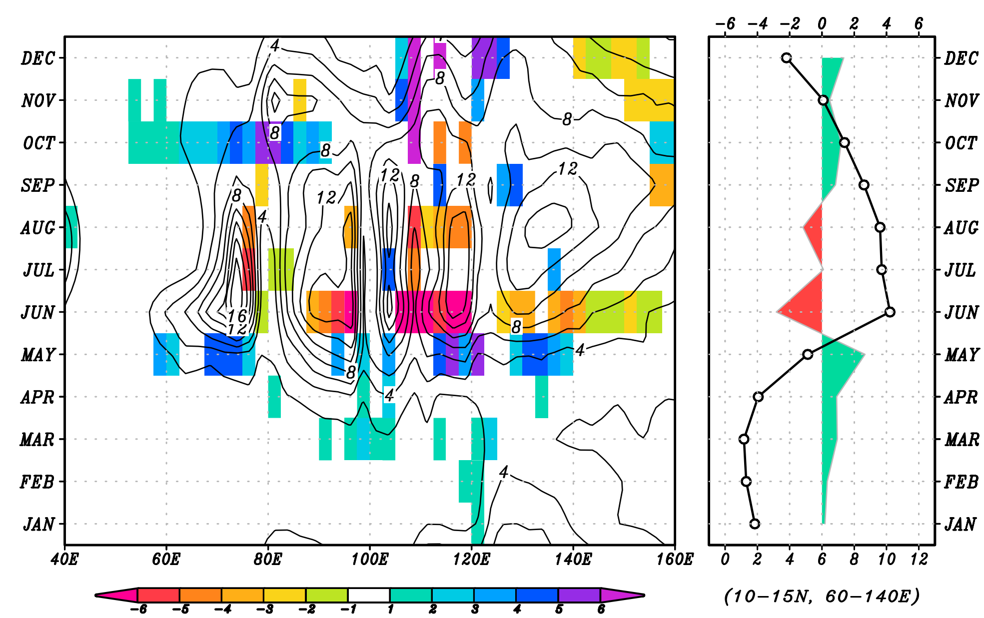

Figure 2. (left) Latitude-time section of trend (shading: mm/day) and climatology (contour: mm/day) of CMAP rainfall along 10–15°N. Shadings are the same as in Figure 1. (right) Time series of trend (shading: top axis) and climatology (line: bottom axis) of rainfall averaged over the area (10–15°N, 60–140°E).

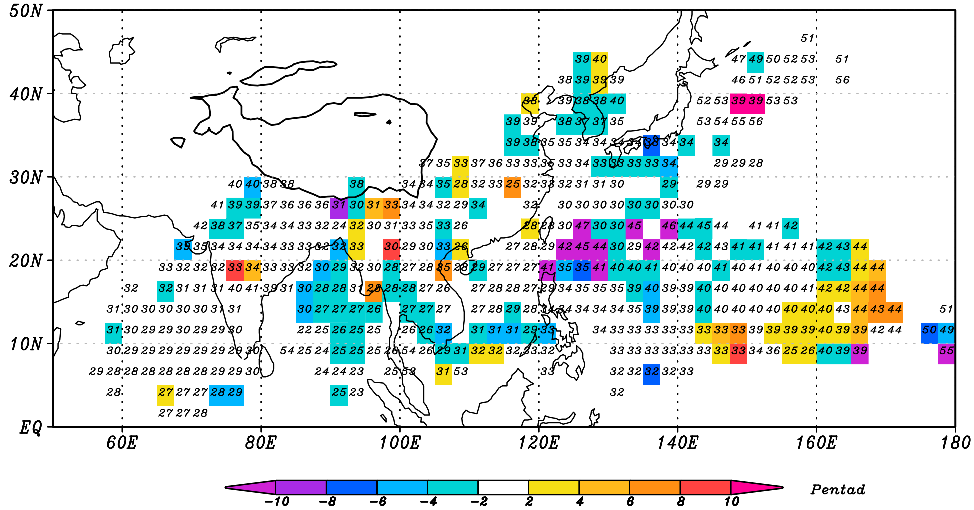

Figure 3. Date of monsoon onset by climatological pentad mean rainfall during 1979–1993 (Digit). The onset pentad was determined by the method of *Wang and LinHo* [2002]; the Julian pentad in which the relative rainfall rate, minus the January mean, exceeds 5 mm/day is defined as the onset pentad. The shading denotes the difference in the monsoon onset between 1994–2008 and 1979–1993 and is shaded for differences more and less than 2 pentads.

July and August does not have a significant trend, although a small decreasing trend in August is visible. This corresponds with the rainfall trend in boreal summer mean (Figure 1d). Another increasing trend over the Arabian Sea in October is also significant. Thus, the Asian monsoon rainfall had a mainly significant trend during the transient phase, especially from boreal spring to summer.

[6] We examined the monsoon onset variability based on the climatological pentad mean rainfall data. We divided the whole analysis period into two equal periods: 1979–1993 and 1994–2008. The definition of the monsoon onset date was the first Julian pentad in which monsoonal rainfall exceeds 5 mm/day following the method of *Wang and LinHo* [2002] The monsoon onset dates over the Bay of Bengal, Indochina Peninsula, and western Pacific around 120–140°E have shifted to approximately 10–15 days earlier in recent decades (Figure 3). Conversely, the monsoon onset over the western-middle Pacific along 160°E has become later by 10–15 days. These advanced onsets of the Southeast Asian summer monsoon (SEAM) and the western North Pacific summer monsoon (WNPM) during recent decades reflect the increasing rainfall trends in May.

3. Possible Factors of the Advanced Monsoon Onset

[7] To analyze possible factors causing the advanced monsoon onset in recent decades, we examined the dynamical

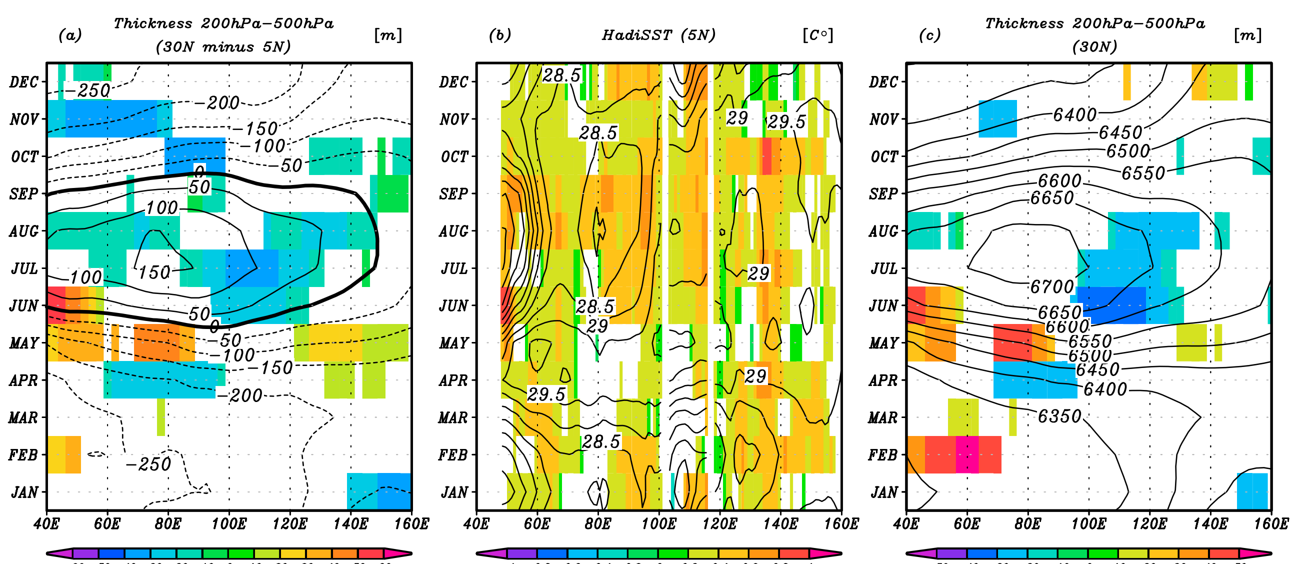

Figure 4. (a) Longitude-time section of the trend (shading: m) and climatology (contour: m) of the difference in atmospheric thickness (200–500 hPa) between land (30°N) and ocean (5°N) areas. Trends are multiplied by 30 (years) for the period 1979–2008. Only those that are significant at 95% level following the Mann-Kendall test are plotted. (b) Same as Figure 4a but for SST along 5°N. (c) Same as Figure 4a but for along 30°N.

heating contrast between land and ocean. The atmospheric thickness between 200 and 500 hPa is an effective index of the meridional thermal contrast in the monsoon region [*Li and Yanai*, 1996; *Ueda and Yasunari*, 1998]. Figure 4a shows the trend of the thermal contrast between land (30°N) and ocean (5°N). A significant warming trend was found mainly in May over the broad scale of the Asian monsoon area, especially along the Tibetan Plateau. Taking into consideration the zero line of this index in the climatology, these warming trends shifted the timing of the heat contrast overturning between land and ocean advance. Hence, the large-scale monsoon likely had an advanced onset. In contrast, after the climatological heat contrast changed sign in June, the trend of heat contrasts turned to cooling in the Asian monsoon region, especially over China. A cooling trend in the upper troposphere over China and the tendency toward increased flood in Yangtze River valley (107°E–120°E, 27°N–32°N) have been reported [*Yu et al.*, 2004] which is consistent with our result in Figure 1d.

[8] Research has also suggested that the trend and long-term variability of the Asian monsoon are closely related to the warming SST trend of the El Niño–Southern Oscillation mode over the tropical Pacific and Indian Ocean [*Yang and Lau*, 2004]. However, these SST warming trends last throughout the year, with little significant seasonal variation (Figure 4b). The heating trends over land (along 30°N) had striking seasonal differences. Warming trends dominated along 40°E and 80°E in May and cooling trends dominated along 110–120°E during boreal summer (Figure 4c). Therefore, we concluded that heating trends over the land area mainly contributed to the trend in the thermal contrast between land and ocean, which reflects continental large-scale monsoon onset variability.

4. Concluding Remarks and Discussions

[9] We examined the long-term trend of the Asian summer monsoon during 1979–2008, with a focus on its strong seasonality. The increasing rainfall trend in May was remarkable over the Arabian Sea, Bay of Bengal, and southeastern monsoon region, which have experienced advanced monsoon onset in recent decades. The trends were, however, nearly reversed in June over the abovementioned region. Of interest is that the Asian monsoonal rainfall in July and August did not show a clear significant trend. The Asian monsoon had a significant trend during the transient phase from boreal spring to summer, in particular. Therefore, the long-term trend of boreal summer mean rainfall significantly differed according to whether it involved May. These long-term trends were also detected in common by using three different rainfall datasets (Figure S1).

[10] The advanced onset and weakening of the SEAM and WNPM during early summer were most likely due to the heat contrast between the Asian landmass and tropical Indian Ocean. The heating trend over the Asian landmass primarily contributed to the heat contrast variability with the persistent SST increase in the Indian Ocean throughout the season. One plausible factor for the warming trend would be dust aerosol loading along the Himalaya-Tibetan Plateau. The accumulation of desert dust and soot aerosols over northern India and the foothills of the Himalayas can enhance the heating in the mid-upper troposphere by the aerosol direct effect (solar absorption) and strengthen the meridional thermal contrast [*Lau and Kim*, 2006; *Lau et al.*, 2006]. The warming temperature trend in the troposphere during recent decades was observed in high-resolution satellite data and was interestingly prominent in the pre-monsoon season with peak in May [*Gautam et al.*, 2009]. This aerosol loading drops with the arrival of monsoon rainfall due to the washout.

[11] We speculate that the thermal contrast induced by dust and aerosols mainly have caused the recent change in the SEAM onset, however, the WNPM and the East Asian monsoon trends could have other possible factors. For instance, the enhancements of the intraseasonal variability and tropical cyclone activity, which are attributed to SST warming over the western Pacific, could be also a stronger trigger of the South China Sea summer monsoon onset [*Kajikawa and Wang*, 2012]. The East Asian monsoon variability could be affected by the thermal condition near surface during late spring [*Zhang and Zuo*, 2011] and anomalous water vapor transport by the easterly associated with the northwestern Pacific subtropical high [*Simmonds et al.*, 1999]. The decreasing rainfall trend in June could be due to the slowing down of northward propagation of the first ISV [*Goswami et al.*, 2010]. Further investigations are needed (1) to elucidate the possible mechanism that produces seasonality in the long-term variation in each monsoon systems and (2) to address whether the remarkable SST increase was due to anthropogenic or natural forcing.

[12] We first noted the significant seasonality in the long-term rainfall trend: the Asian monsoon onset has advanced in recent decades. Our results strongly suggest that the responses of the Asian monsoon to natural and/or anthropogenic forcing may differ largely from season to season. Hence, we recommend that attention be given to the seasonality and seasonal transition phase in future climate change research, including the assessment of state-of-the-art climate model simulations. The use of both seasonal mean and monthly mean data is also recommended for a better understanding and assessment of the seasonal transition phase, which is important for clarifying the impact on human society.

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