Different impacts of the two types of El Niño on Asian summer monsoon onset

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Abstract
In this study, we investigate the features of Asian summer monsoon onset during the decaying phases of central Pacific (CP) and eastern Pacific (EP) types of El Niño. The Asian summer monsoon onset is late during the EP El Niño while it is generally normal during the CP El Niño. Compared to the CP El Niño, the EP El Niño exerts a stronger impact on the climate over the Indian Ocean and the western North Pacific. Warmer sea surface temperature (SST) develops in boreal spring in the southern Indian Ocean and thus forms a large cross-equatorial SST gradient during the EP El Niño, which induces asymmetric patterns of winds and precipitation over the Indian Ocean. The asymmetric precipitation and circulation patterns contribute to a late monsoon onset. In addition, the anomalous anticyclone over the western North Pacific during the EP El Niño also contributes to late onset of the monsoon.

Keywords: monsoon onset, two types of El Niño, Indian Ocean asymmetric mode,

1. Introduction
The Asian monsoon affects more than sixty per cent of the world’s population. Much effort has been devoted to understanding the variations of the Asian monsoon (e.g. Webster et al 1998, Yang and Lau 2006, Boos and Kuang 2010, Wu et al 2012). The El Niño-Southern Oscillation (ENSO) and the Asian monsoon exhibit strong interactions (e.g. Webster and Yang 1992, Lau and Wang 2006) on a wide range of time scales (Lau and Yang 1997, Yang and Lau 2006, Jiang and Li 2011, Jiang et al 2013a, 2013b). El Niño is traditionally recognized as a warming in the eastern-central equatorial Pacific (e.g. Trenberth 1997, Yu and Kao 2007). However, in some years, a substantial warming develops in the central Pacific (CP), which has been referred to as the CP El Niño (Yu and Kao 2007, Kao and Yu 2009), El Niño Modoki (Ashok et al 2007), dateline El Niño (Larkin and Harrison 2005), or warm pool El Niño (Kug et al 2009), while the conventional El Niño is referred to as the eastern Pacific (EP) El Niño (Yu and Kao 2007, Kao and Yu 2009), or cold tongue El Niño (Kug et al 2009). The two types of El Niño have different climate impacts (Weng et al 2007, 2009, Yuan and Yang 2012, Yuan et al 2012, Zhang et al 2011). The Asian monsoon behaves in different ways during the whole life cycle of the CP and EP types of El Niño (Weng et al 2007, 2009, Yuan and Yang 2012). Both Asian summer and winter monsoon tends to be weaker (stronger) than normal during the developing (decaying) phase of the CP (EP) El Niño (Weng et al 2007, 2009, Yuan and Yang 2012). The East Asian winter monsoon also shows distinct differences during the two types of El Niño (Weng et al 2009, Yuan and Yang 2012).

Most previous studies focus on the seasonal climate impacts of the two types of El Niño. The Asian monsoon exhibits a strong annual cycle, and one of the most fascinating features is the abrupt onset of the Asian summer monsoon
Table 1. Climatological mean monsoon onset dates (unit: pentad) in the Bay of Bengal, the South China Sea, the Indo-China Peninsula, and the Indian Peninsula with different precipitation thresholds (unit: mm day$^{-1}$), and difference of mean monsoon onset date between EP (CP) El Niño years and climatology. Bold font denotes the values exceeding the 90% confidence level.

|       | BoB | SCS | ICP | IP |
|-------|-----|-----|-----|----|
| Threshold | 8   | 7   | 9   | 7  |
| Clim   | 26.1| 25.3| 26.5| 29.3|
| EP-Clim| 1.4 | 1.5 | 1.0 | 4.2 |
| CP-Clim| 0.8 | -0.4| 1.2 | 0.9 |

(Lau and Li 1984, Lau and Yang 1997). Factors responsible for the interannual variation of the Asian monsoon include local sea surface temperature (SST; Jiang and Li 2011), local meridional tropospheric temperature gradient (Li and Yanai 1996), thermal conditions over the Tibet Plateau (Wu and Zhang 1998), atmospheric intraseasonal oscillation (Zhang et al 2002), and remote forcing of tropical Pacific SST (Lau and Yang 1997, Wu and Wang 2000). Although the climatological onset dates vary with regions, the interannual variability of regional monsoon onset over most of Asia is partly affected by the ENSO (Joseph et al 1994, Lau and Yang 1997, Wu and Wang 2000, Zhang et al 2002, Mao and Wu 2007). An El Niño (La Niña) event is generally followed by a late (an early) Asian summer monsoon onset. The two types of El Niño exert different impacts on the seasonal mean climate. Do they also exert different impacts on monsoon onset? In this study, we analyze the features of Asian summer monsoon onset during the EP and CP El Niño decaying phases, as well as the underlying atmospheric and ocean processes.

2. Data and method

Datasets used in this study include the monthly SST data from the Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST, Rayner et al 2003), monthly atmospheric reanalysis data from the National Centers for Environmental Prediction and the Department of Energy Atmospheric Model Intercomparison Project-II Reanalysis (Kanamitsu et al 2002), and the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP, Xie and Arkin 1997). We focus on the period 1979–2010. Following Yuet et al (2012, table 1), and based on the consensus of three different identification methods (Kao and Yu 2009, Yeh et al 2009, Ashok et al 2007), four EP El Niño events (1982–1983, 1986–1987, 1997–1998, and 2006–2007) and six CP El Niño events (1987–1988, 1991–1992, 1994–1995, 2002–2003, 2004–2005, and 2009–2010) occurred during the analysis period. We analyze the monsoon onset during the El Niño decaying years. The Student $t$-test is used to assess the statistical significance of the results obtained.

3. Results

Figure 1 shows the seasonal evolution of zonal average precipitation along the Asian monsoon region (75°–120°E). A three-point smoothing is applied to the rainfall data along the time dimension in figure 1. In boreal winter, maximum precipitation is generally located in the southern hemisphere around 10°S. As the sun moves to the northern hemisphere, maximum precipitation abruptly shifts to the equator, and then rapidly jumps to around 10°N in mid-May (pentad 27). The precipitation maximum is maintained in the region until early October, when it begins a southward movement. The
annual cycle of precipitation in the Asian monsoon region is different from those in the tropical central and eastern Pacific and the tropical Atlantic, where trade winds prevail and the precipitation maximum is mostly located to the north of the equator all year around (Jiang and Li 2011). The abrupt northward jump of the precipitation maximum from the equator to around 10°N indicates the Asian summer monsoon onset (Jiang and Li 2011). Indeed, the monsoon onset features are not only local changes in rainfall, winds, and other variables, but also changes in the interactions between the northern and southern hemispheres (Zeng and Li 2002). For example, the thermal contrast in the tropics between the northern and southern hemispheres and the cross-equatorial flow over the Indian Ocean (IO) are different after the monsoon onset (e.g. Li and Yanai 1996). The annual cycles of precipitation during the two types of El Niño are generally similar to the climatology, in spite of some differences. Here, we focus only on monsoon onset. For the EP El Niño, the precipitation maximum is generally located at either the equator or around 10°S prior to a northward jump to around 10°N in early June (pentad 32), after which time it remains around this latitude until early October. For the CP El Niño, the abrupt northward jump of precipitation from the equator to around 10°N occurs in mid-May (pentad 28). The dates of the northward jump of the precipitation maximum indicate that the Asian summer monsoon onset during the CP El Niño is close to the climatology, but it is delayed by about five pentads during the EP El Niño.

The Asian summer monsoon onset processes are different for different regions. To further illustrate the different features of monsoon onset during the two types of El Niño, we now analyze the local features of monsoon onset. The seasonal evolutions of regional average precipitation for climatology and the two types of El Niño in the Bay of Bengal (BoB; 5°–15°N/75°–120°E), the South China Sea (SCS; 5°–15°N/110°–120°E), the Indo-China Peninsula (ICP; 5°–15°N/100°–110°E), and the Indian Peninsula (IP; 5°–15°N/70°–80°E) are presented in figure 2. The Asian summer monsoon onset first occurs in the BoB in late April or early May (Wang and LinHo 2002, Li and Zhang 2009, Jiang and Li 2011). As shown in figure 2(a), climatological precipitation exceeds 8 mm day⁻¹ in the 25th pentad and persists for more than three months. Thus, the precipitation exceeding 8 mm day⁻¹ can be regarded as the threshold for monsoon onset in the BoB. Precipitation during the two types of El Niño increases rapidly from the 22nd pentad and exceeds 8 mm day⁻¹ by the 25th pentad. After that, the precipitation during the EP El Niño decreases abruptly and is less than 8 mm day⁻¹ during pentades 27–29. It then exceeds 8 mm day⁻¹ again at pentad 30 and persists for more than one month. In contrast, the precipitation during the CP El Niño is persistently higher than 8 mm day⁻¹. The monsoon onset is generally defined as when the precipitation exceeds a threshold and then persists for at least a certain period of time, e.g. 4 pentads (Wang et al 2004, Li and Zhang 2009). Seasonal evolutions of rainfall of the...
composite of the four EP El Niño years between 1979 and 2010, indicate that the first time when rainfall amount exceeds 8 mm day$^{-1}$ is strongly affected by a ‘bogus onset’ in 2007 (e.g., Flatau et al. 2003, Joseph et al. 2006; figure not shown). As a result, the monsoon onset date over the BoB during the EP El Niño should be considered to be the 30th pentad. The PCS monsoon onset occurs climatologically around the 27th or 28th pentad (Wang et al. 2004, Li and Zhang 2009), when precipitation exceeds 7 mm day$^{-1}$ (figure 2(c)). The variation of precipitation during the two types of El Niño indicates that the PCS monsoon onset is delayed by two pentads during the CP El Niño, and five pentads during the EP El Niño. Precipitation in the ICP is lower than that in the BoB and the SCS, thus the precipitation threshold for the monsoon onset is also lower, with a precipitation slightly over than 5 mm day$^{-1}$ in the 26th pentad when local monsoon onset occurs (Wang and LinHo 2002, Li and Zhang 2009). The monsoon onset date in the ICP during the CP El Niño is close to the climatology, while it is delayed by three pentads during the EP El Niño. In the IP, precipitation increases rapidly from the 28th pentad and exceeds 8 mm day$^{-1}$ around pentad 30, when climatological monsoon onset is detected by previous studies (e.g., Joseph et al. 1994, Wang and LinHo 2002, Li and Zhang 2009). Comparison of seasonal evolution of regional precipitation in the IP between the climatology and the two types of El Niño indicates that the monsoon onset date is close to climatology during the CP El Niño, while it is delayed for at least two pentads during the EP El Niño.

The above analyses are based on composite regional mean precipitation. To further illustrate anomalies of monsoon onset during the two types of El Niño, we define the monsoon onset date of individual years and analyze the differences of mean monsoon onset date between the two types of El Niño years and the climatology. Monsoon onset date is defined as the first pentad after the 20th pentad with rainfall exceeding a threshold value where the heavy rainfall lasts for at least two pentads for the following consecutive three pentads. Based on the climatological monsoon onset analyses, the precipitation thresholds used for the BoB, the SCS, the ICP, and the IP are 8 mm day$^{-1}$, 7 mm day$^{-1}$, 5 mm day$^{-1}$, and 8 mm day$^{-1}$, respectively. The climatological mean monsoon onset dates based the definition are pentad 26.1, 29.3, 26.7, and 30.6 for the BoB, the SCS, the ICP, and the IP, respectively, which are almost the same as the dates identified by the composite regional mean precipitation. The differences of mean monsoon onset date between the two types of El Niño years and the climatology indicate that monsoon onset over the four regions is late during the EP El Niño (table 1). But only the change in the SCS monsoon onset is statistically significant at the 90% level. During the CP El Niño, the monsoon onset is later than normal over the BoB and the SCS and earlier than normal over the ICP and the IP; however these changes are not statistically significant at the 90% level.

The monsoon onset date and the differences identified by the definition may be sensitive to the threshold. To examine this we test the sensitivity of the monsoon onset date to a 1 mm day$^{-1}$ increase or decrease in the threshold, for the different regions. The results in table 1 indicate that a smaller threshold generally causes an earlier monsoon onset. The delayed monsoon onset during the EP El Niño is generally not sensitive to the threshold, but the statistical significance of the change in monsoon onset date is sensitive to the threshold over the SCS and the IP. During the CP El Niño, the anomalies of monsoon onset dates are general smaller and not statistically significant for all the thresholds.

Because the monsoon onset dates depend on the definitions, we further analyze the composite wind anomalies in the monsoon transition month. Composite anomalies of April and May SST and 850-hPa winds during the decay phase of the EP and CP El Niño are presented in figure 3. The 850-hPa wind anomaly during the decay phase of the EP El Niño is stronger than that during the CP El Niño. An asymmetric wind pattern emerges over the tropical IO in April during the decay phase of the EP El Niño, with significant easterly anomalies from the Philippine Sea to eastern Africa and westerlies over the southern tropical IO. In May, the easterly anomalies get stronger while the westerly anomalies become weak. Easterlies prevail in monsoon regions prior to monsoon onset, while westerlies prevail after monsoon onset. Thus, the easterly wind anomaly from the Philippine Sea to the Arabian Sea during the decay phase of the CP El Niño is consistent with the late monsoon onset. On the other hand, a significant anticyclone over the western North Pacific in May is found during the decay phase of the EP El Niño, consistent with the delayed SCS monsoon onset, because the SCS monsoon onset corresponds to an eastward retreat of the western Pacific subtropical high from the SCS to the Philippine Sea. The 850-hPa wind anomaly during the decay phase of the CP El Niño, however, is significant only over parts of the Asian summer monsoon region and does not exhibit obvious anomalies of large-scale circulation.

Why does the Asian summer monsoon onset show different responses to the two types of El Niño? Spatial patterns of SST anomaly during the two types of El Niño share common features, with positive values in the IO and negative values in the western North Pacific. However, the magnitude of SST anomaly during the CP El Niño is small and insignificant while it is large and significant during the EP El Niño, consistent with the wind anomaly (figure 3). It is worth noting that the SST anomalies in the IO exhibit a strong cross-equator SST gradient during EP El Niño, especially in April, with warmer SST in the southern IO. Based on observational data, Jiang and Li (2011) reported that such an SST gradient favors a late monsoon onset by changing wind convergence and humidity in the atmospheric boundary layer. The anomalous SST pattern can induce enhanced (reduced) convection in the southern (northern) tropical IO (Wu et al. 2008, Chakravorty et al. 2013). Indeed, the composite precipitation during the EP El Niño decreases (increases) in the northern (southern) IO in both April and May; while it only exhibits a slight decrease in the eastern IO in April and an increase in the central IO in May during the EP El Niño (figure not shown). In addition, results from numerical models also indicate that the SST pattern could force a late Indian monsoon (Annamalai et al. 2005).
Figure 3. Composite anomalies of April SST (°C; shadings) and 850-hPa winds (m s$^{-1}$; vectors) for (a) eastern Pacific El Niño decaying years and (b) central Pacific El Niño decaying years. (c), (d) are respectively the same as (a) and (b), but for May. Only the values above the 90% confidence level are shown in the maps. The boxes in (b) indicate the locations of the Bay of Bengal (5°–15°N/75°–120°E), the South China Sea (5°–15°N/110°–120°E), the Indo-China Peninsula (5°–15°N/100°–110°E), and the Indian Peninsula (5°–15°N/70°–80°E).

Figure 4. Composite anomalies of meridional circulation (pressure vertical velocity is multiplied by $-100.0$) along 70°–120°E for eastern Pacific El Niño decaying years and central Pacific El Niño decaying years. Either meridional wind velocity or vertical velocity exceeding the 90% confidence level is shaded. (a) EP El Niño April, (b) CP El Niño April, (c) EP El Niño May and (d) CP El Niño May.

The Hadley circulation is also different between the two types of El Niño (Feng and Li 2013). Composite average meridional circulations over the Asian monsoon region during the two types of El Niño exhibit distinct differences (figure 4). A well formed significant meridional circulation can be found during the EP El Niño: air ascends between 10°S and
20°S, moves northward to the northern hemisphere in the upper troposphere, then descends around 10°N, and finally returns to the southern hemisphere in the lower troposphere. This anomalous meridional circulation is consistent with the asymmetrical precipitation in the IO during the EP El Niño (Wu et al. 2008). The anomalous meridional circulation in April is stronger than that in May, which may be ascribed to the stronger cross-equatorial SST gradient in April (Lindzen and Nigam 1987). In addition, air around the 25°N also rises, moves southward in the upper troposphere, and finally descends around 10°N in April. The descending air flow around 10°N during the EP El Niño favors a late monsoon onset. During CP El Niño, descending air flow can also be seen between the equator and 10°N in April while ascending air flow is found around 10°S in May. These anomalous circulations, however, are insignificant.

The above analyses indicate that the asymmetric patterns of convection and circulation play an important role in the late monsoon onset during the EP El Niño. These asymmetric patterns and the anomalous SST pattern have been reported by previous studies (Wu et al. 2008, Chakravorty et al. 2013), namely an air–sea coupling mode in the tropical IO (Wu et al. 2008). This mode presents during some but not all El Niño events. It is well developed when El Niño co-occurs with a positive IO dipole (Chakravorty et al. 2013). Indeed, a positive IO dipole is only found to co-occur with the EP El Niño, and does not co-occur with the CP El Niño (Kao and Yu 2009, Yuan et al. 2012).

Besides the asymmetric mode, the anomalous anticyclone over the western North Pacific also favors a late monsoon, especially in May during the EP El Niño. On the one hand, the western North Pacific directly affects the monsoon onset in the ICP and the SCS. On the other hand, the northeasterly anomalies over the northern IO are mainly induced by the anticyclone over the western North Pacific in May, when the cross-equatorial SST gradient is weak in the IO (Chakravorty et al. 2013). The anticyclone can be regarded as a Rossby wave response to the depressed convection over the western North Pacific, caused by the underlying cold SST (figure 3, Wang et al. 2000, Jiang et al. 2013c).

4. Summary and discussion

Many studies categorize El Niño into two types: the EP El Niño and the CP El Niño, which exert distinctly different climate impacts. Previous studies mostly focus on the difference in seasonal mean climate. Little is known about the climate impacts of the two types of El Niño on the annual cycle. In this study, we analyze the Asian summer monsoon onset during the two types of El Niño decaying phase. Results show that a late monsoon onset occurs during the EP El Niño while the monsoon onset is generally normal during the CP El Niño. The climate anomalies in April and May are distinctly different during the two types of El Niño. The magnitude of anomalies in SST, precipitation, and circulations over the IO and the western North Pacific during the EP El Niño is larger than that during the CP El Niño. The asymmetric anomalies of precipitation and 850-hPa winds over the IO, which develop during the EP El Niño, play an important role in the delayed monsoon onset. In addition, the anticyclone over the western North Pacific during the EP El Niño also contributes to the late monsoon onset.

The monsoon onset date identified by the regional mean rainfall with a threshold may depend on the selected threshold. As a result we have tested the sensitivity of monsoon onset to threshold in the BoB, the SCS, the IIP, and the ICP. The delayed monsoon onset in the SCS and the IP during the decay phase of the EP El Niño is not sensitive to the thresholds, while it is somewhat sensitive to the thresholds in the BoB and the ICP. But the composite wind anomalies from the Arabian Sea to the SCS (figure 3) indicate that monsoon onset in all the regions may be delayed during the decay phase of the EP El Niño. Thus, further studies focused on regional monsoon onset during the two types of El Niño are warranted.

In this study, we have just focused on the Asian summer monsoon onset over the tropics. The Asian monsoon also includes a subtropical component over northern East Asia, which features a stepwise northward onset and is different from the monsoon in the tropics in many aspects (e.g. Li and Zeng 2003, Ding 2004, He et al. 2008). Further analyses are needed to examine the impacts of the two types of El Niño on the onset of the East Asian subtropical monsoon. The Asian summer monsoon onset is also affected by the atmospheric intraseasonal oscillation and land processes (Wu and Zhang 1998, Zhang et al. 2002). Thus, there may exist other ways by which the two types of El Niño exert different impacts on the Asian summer monsoon onset.

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