Objective determination of the onset and withdrawal of the South China Sea summer monsoon

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Abstract

Determining the timing (i.e. onset and withdrawal) of monsoon season precisely and objectively is an important yet difficult task. Conventional methods mainly define the monsoon timing as the date when the selected atmospheric variables (e.g. rainfall and wind) exceed an arbitrary threshold. These methods present little explicit justification and are subjective and sensitive to the fluctuation of the selected series. In this study, we propose an objective method to determine the onset and withdrawal of the South China Sea summer monsoon (SCSSM) using the cumulative low-level zonal wind. Our proposed approach provides an easy, objective, and applicable method that is recommended for the detection of the timing of monsoon season. On the basis of the proposed definition, the SCSSM onset and withdrawal are determined, and their accompanying processes are also examined in this paper. Both onset and withdrawal of SCSSM exhibit strong variability, and the El Niño–Southern Oscillation plays an important role. Via the modification of the western North Pacific subtropical high, a preceding El Niño (La Niña) event can delay (advance) the monsoon onset and advance (delay) the monsoon withdrawal.

Keywords: objective determination; South China Sea summer monsoon; monsoon onset and withdrawal; El Niño–Southern Oscillation; western North Pacific subtropical high

I. Introduction

Summer monsoon onset and withdrawal indicate the beginning and end of the summer rainy season (Tao and Chen, 1987; Wang et al., 2004; Ding and Chan, 2005), respectively, significantly affecting agriculture and water resource management decisions. The onset and withdrawal timing of the monsoon season should be correctly determined and predicted. As one important component of the Asian summer monsoon (Tao and Chen, 1987), the onset of the South China Sea summer monsoon (SCSSM) indicates the end of dry season and beginning of the summer rainy season over East Asia (Wang et al., 2004; Ding and Chan, 2005; Luo et al., 2016), whereas its withdrawal indicates the end of the rainy season.

A wide array of variables and methods has been proposed to determine the timing of monsoon transition (Wang et al., 2004; Ding and Chan, 2005), including precipitation and its proxies, such as outgoing long-wave radiation (OLR), upper-tropospheric brightness temperature, high cloud amount, high reflective cloud (Tanaka, 1992; Yan, 1997; Zhu et al., 2001), surface or low-level winds (Lu and Chan, 1999; He et al., 2001; Wang et al., 2004), or a combination of convection and winds (Li et al., 1999; Kueh and Lin, 2001). For instance, Wang et al. (2004) emphasized a firm establishment of steady westerly over the SCS and defined the SCSSM onset as the date when low-level wind changes from the easterly to the westerly wind. As the SCSSM onsets, low-level wind changes its direction from easterly to westerly. However, these indices are subjective (at least to some extent) and exhibit strong fluctuations, thereby causing difficulty in determining the timing of the monsoon circulation. Accordingly, an easy, objective, and applicable definition should be proposed.

Moreover, previous studies on monsoon timing mainly focused on monsoon onset (Zhou and Chan, 2007; Kajikawa and Wang, 2012; Luo et al., 2016; Zhu and Li, 2017), with a few on the monsoon withdrawal, particularly its variability (Syroka and Toumi, 2004; Li and Zhang, 2009; Stolbova et al., 2016). El Niño–Southern Oscillation (ENSO) is one of the major factors affecting the variabilities of Asian monsoons (Huang et al., 2004; Yuan and Yang, 2012; Chen et al., 2013). For example, previous studies show that the SCSSM onset tends to occur later (earlier) during El Niño (La Niña) decaying summer (Zhou and Chan, 2007; Ding et al., 2016; Luo et al., 2016). Besides the monsoon onset, the monsoon withdrawal is also significant to societies since it signals the termination of the summer rainy season (Luo, 2014; Stolbova et al., 2016). However, the behaviors associated with the monsoon withdrawal and its variability have yet been investigated.

In the present study, we first propose an objective approach to determine the onset and withdrawal timing
of the SCSSM. Subsequently, we investigate the inter-annual variability of the onset and withdrawal dates and the possible influences of ENSO on these variabilities. The remainder of this paper is organized as follows. In Section 2, the dataset used in this study is introduced, and an objective method to determine the SCSSM onset is proposed. The analysis results are presented and discussed in Section 3. The concluding remarks are summarized in Section 4.

2. Dataset and methodology

2.1. Dataset

The primary dataset used in this study is obtained from the NCEP-DOE Reanalysis 2 data (Kanamitsu et al., 2002), covering the study period of 1979–2016, and the horizontal resolution of this dataset is 2.5° × 2.5°. The observational patterns presented in this study are obtained from daily and monthly variables of horizontal winds and 500-mb geopotential height. Monthly SST data from the NOAA Extended Reconstructed Sea Surface Temperature (ERSST) v4 with the 2° × 2° horizontal resolution (Huang et al., 2015) is also employed in our study. Anomalies are obtained by removing the climatological average in the period 1981–2010.

2.2. Objective determination of the monsoon onset and withdrawal dates

As suggested by previous studies, the SCSSM circulation is normally characterized by low-level zonal wind, e.g. 850-mb (Wang et al., 2004; Kajikawa and Wang, 2012). Considering that the indicator of wind circulation has less random noise and variation than that of rainfall, we select the 850-mb zonal wind averaged in the central SCS region (110°–120°E, 5°–15°N, noted as \( U_{SCS} \)) as the SCSSM circulation index to characterize the transition of monsoon seasons over the SCS.

Wang et al. (2004) defined the SCSSM onset as the first pentad after April 25 that satisfies the following criteria: (1) \( U_{SCS} > 0 \) in the onset pentad, (2) \( U_{SCS} > 0 \) for at least three pentads in the subsequent four pentads and the accumulative four-pentad average \( U_{SCS} > 1 \) m s\(^{-1}\). Kajikawa and Wang (2012) extended this definition to a daily-series-based format and defined the onset date as the first day after 25 April that satisfies the above criteria. Nevertheless, the definition by Wang et al. (2004) and Kajikawa and Wang (2012) is subjective to some degree; for example, the selections of 1 m s\(^{-1}\) wind speed for at least four-pentad (or 20-day) duration are debatable. Moreover, the daily \( U_{SCS} \) index (and its 5-day smoothed series) exhibits strong fluctuation while the monsoon withdrawal process is relatively slow, so that this definition is inapplicable for determining monsoon withdrawal. Therefore, an objective and unified determination for both monsoon onset and withdrawal is needed.

Previous studies show that cumulative series of atmospheric variables (e.g. precipitation) has less fluctuation and can be used to characterize the rainy season timing over India (Cook and Buckley, 2009; Noska and Misra, 2016). We accumulate the \( U_{SCS} \) values starting from January 1 to every calendar day for each year (February 29 for leap years are removed), and obtain daily cumulative \( U_{SCS} \) series. By examining the cumulative series (Figure 1), we notice that the alternation of wind direction of the monsoon circulation becomes more distinct, and monsoon timing can be easily identified from this cumulative \( U_{SCS} \) series.

For illustration, Figure 1(a) and (b) show the original and cumulative \( U_{SCS} \), respectively. The cumulative \( U_{SCS} \) for day \( d \) of year \( y \), denoted as \( U'_{y}(d) \) is computed as follows:

\[
U'_{y}(d) = \sum_{i=1}^{d} U_{y}(i)
\]  

where \( U_{y}(i) \) is the daily zonal wind for day \( i \) of year \( y \). Figure 1(b) shows that the onset and withdrawal of monsoon in all years are characterized by a remarkable...
‘valley’ and ‘peak’, respectively, in the series of cumulative zonal wind. During the period before the ‘valley’, the cumulative $U_{SCS}$ gradually descends, thereby suggesting that easterly winds dominate the region in this period, which is characterized as winter monsoon season. On the day of ‘valley’, the cumulative $U_{SCS}$ reverses its signal from descending to ascending, thereby indicating that the zonal wind reverses its signal from easterly to westerly. During the period after the ‘valley’, the cumulative $U_{SCS}$ ascends, thereby indicating that westerly wind begins to dominate the region. This period is the summer monsoon season.

In addition to the significant ‘peak-valley’ pattern in the cumulative $U_{SCS}$, the daily cumulative $U_{SCS}$ also exhibits considerably less fluctuation than the original $U_{SCS}$ series. The cumulative $U_{SCS}$ can be easily used to define the onset and withdrawal dates of the monsoon season. The monsoon onset and withdrawal are defined as the day after the ‘valley’ and ‘peak’, respectively, of the cumulative $U_{SCS}$ series. According to this definition, we calculate the onset and withdrawal dates of the SCSSM circulation in the period of 1979–2016, and the results are presented in the next section.

3. Results

3.1. Monsoon onset and withdrawal dates

The onset and withdrawal dates of the SCSSM are determined by the valleys and peaks of the cumulative $U_{SCS}$ series starting from January 1 of all the years. Yearly SCSSM onset and withdrawal dates are shown in Figure 2. The SCSSM onset occurs on May 24 on average. Our results of monsoon onset dates are also compared with those based on the method of Kajikawa and Wang (2012), and a significant correlation of 0.64 ($P < 0.01$) is observed. Notably, the definition of Wang et al. (2004) or its daily-based format (i.e., Kajikawa and Wang (2012)) is not applicable to determine the monsoon withdrawal because of the substantially strong fluctuations when the monsoon retreats (Figure 1(a)). On the basis of our proposed definition, the climatological withdrawal date of SCSSM is October 18 on average.

Figure 2(a) illustrates that the SCSSM onset exhibits significant interannual and decadal changes in the early 1990s (i.e. 1994). SCSSM onset commenced later before the early 1990s and earlier after the early 1990s, and it became later in recent years. The decadal change in the 1990s has been found related to the enhanced intraseasonal variability and tropical cyclone activity over western Pacific (Kajikawa and Wang, 2012). Besides, Xiang and Wang (2013) suggested that the advanced monsoon onset since the 1990s is associated with a La Niña-like cooling in the Pacific basin. Compared with the monsoon onset, monsoon withdrawal exhibits less decadal variation but strong interannual variability. The interannual variability of monsoon timing is likely affected by ENSO, as discussed in the following sub-section.

3.2. Interannual variability of the monsoon onset and withdrawal

ENSO plays an important role in modulating the variability of Asian monsoons (Wu and Wang, 2002; Lau and Nath, 2006). ENSO can also affect the onset dates of the monsoon circulation (Zhou and Chan, 2007; Luo et al., 2016). In this sub-section, we proceed to re-visit the relationship between this event and the SCSSM onset based on our determination method, and to examine the possible relationship between ENSO and the SCSSM withdrawal. El Niño (La Niña) is defined as when the 3-month smoothed Nino3.4 index is above (below) +0.5 °C (−0.5 °C) for at least five consecutive months.

3.2.1. Monsoon onset variability

We first calculate the correlation between the monsoon timing and the Niño 3.4 index from the preceding summer season to the following summer season (Figure 3(a)). The SCSSM onset holds a significantly positive correlation with the preceding winter Nino3.4 index (i.e. 0.34), implying that a preceding El Niño (La Niña) can delay (advance) the onset date of SCSSM. Such relationship can be clearly observed in the scatter plot of monsoon onset dates versus the Niño 3.4 index in the preceding winter (Figure 3(c)). As shown in Figure 3(e), an El Niño-like SST pattern appears in the Pacific Ocean, and the highest correlations are concentrated in the central tropical Pacific Ocean, implying an important role of a central Pacific El Niño in modulating the SCSSM onset. The relationship between ENSO and monsoon onset found here agrees with those in previous studies (Zhou and Chan, 2007; Wang et al., 2013; Ding et al., 2016; Luo et al., 2016). Recent studies also suggest that central Pacific and
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30°N 20°N 10°N 0° 10°S 20°S 30°S
30°N Corr. [MOD, DJF(0) SSTA]

Monsoon onset date Correlation
Correlation Monsoon withdrawal date
Corr. [MOD, Nino3.4]
Time lag
JJA(–1) SON(–1) DJF(0) MAM(0) JJA(0) SON(0) DJF(+1) MAM(+1) JJA(–1)

DJF(0) Nino3.4
–0.5
–2
0
01 Jul
20 Jun
10 May
01 May
20 Apr
10 Apr
1
2
–2
–1 0 1 2 –2 –1 0 1 2

0.5
0.4
0.3
0.2
0.1
0
–0.1
–0.2
–0.3
–0.4
–0.5
20 Nov
10 Nov
01 Nov
20 Oct
10 Oct
01 Oct
20 Sep
10 Sep

Figure 3. Relationship of the SCSSM (left) onset and (right) withdrawal dates with the Niño3.4 index and sea surface temperature anomaly (SSTA). (a) and (b) Time–lag correlation with the Niño 3.4 index; (c) and (d) scatter plots of (left) the onset date versus the preceding winter Niño 3.4 index and (right) the withdrawal date versus the concurrent summer Niño 3.4 index; (d) and (e) correlation of the onset and withdrawal dates with the preceding winter and summer SSTA, respectively. In (a) and (b), –1 (+1) denotes the year preceding (following) the SCSSM onset and withdrawal, and thick (thin) dashed horizontal line denotes significance at the 99% (95%) confidence interval. Numbers in (c) and (d) denote the correlation coefficients, and dashed lines denote the fitted lines. Thick contour in (d) and (e) denotes significant correlation at the 95% confidence interval.

traditional eastern Pacific ENSO events have different influences on the East Asian climate (Yuan and Yang, 2012), and the manifestation of central Pacific El Niño is found to be associated with the decadal change of the SCSSM onset since the early 1990s (Ding et al., 2016).

The influences of the preceding winter ENSO on the SCSSM onset are via the modification of the WNPSH and anticyclone (Figure 4). Vectors in Figure 4 depict the differences in low-level horizontal wind between El Niño and La Niña summers (i.e. El Niño minus La Nina), and the contours denote the composite mean of 500-mb geopotential height during El Niño (red) and La Niña (blue). Figure 4 shows that Niño induces an anomalous anticyclone covers the SCS and Philippine Sea region. The WNPSH is stronger and more extended, covering more regions during Niño than La Niña summers. This strengthened (weakened) subtropical high and the Philippine Sea anticyclone induced by preceding El Niño (La Niña) event can prevent (favor) a westerly flow from the Indian Ocean, thus resulting in a late (an early) SCSSM onset.

3.2.2. Monsoon withdrawal variability

Compared with the SCSSM onset, the withdrawal timing presents a stronger correlation with Niño 3.4 index (Figures 3(b)–(e)) and tropical Pacific SST (Figure 3(f)). Figure 3(b) shows that a strong negative correlation exists between the monsoon withdrawal timing and the Niño 3.4 index. In particular, the Niño 3.4 index in the concurrent summer season displays the strongest negative correlation (Figure 3(d)), i.e.
−0.41; this result suggests that the SCSSM withdrawal is significantly modulated by the summer ENSO, and an El Niño (La Niña) can advance (delay) the SCSSM withdrawal. The correlation of summer SST and monsoon withdrawal also shows a distinguishable La Niña pattern (Figure 3(f)), further proving the role of summer ENSO in affecting the SCSSM withdrawal. The modulation of ENSO on the SCSSM withdrawal is likely via the modification of WNPSH. Figure 5 illustrates the composite patterns of 500-mb geopotential height in September, October, and November of El Niño and La Niña years. Compared with La Niña cases, WNPSH is located more southward in September and October (i.e. before the monsoon withdrawal)
of El Niño summers. The southward-displacement of WNPSh indicates that WNPSh retreats earlier during El Niño than La Niña, thus leading to an earlier withdrawal of the summer monsoon. As compared to El Niño, WNPSh during La Niña is located more northward before and during the monsoon withdrawal (i.e. September, October, and November). This northward displacement indicates that the southward retirement of WNPSh during La Niña is later than El Niño, thereby resulting in a later withdrawal of the summer monsoon. Besides, the plausibly different impacts of decaying and developing ENSO on monsoon withdrawal are also examined, and we notice that both decaying and developing El Niño (La Niña) can advance (delay) the monsoon withdrawal via the modification of WNPSh.

4. Summary

In this study, we propose an objective and easy approach to determine the SCSSM timing. This proposed method offers several advantages. First, a prior arbitrary and subjective thresholds are not required. Instead, it is an objective method for determining the monsoon onset and withdrawal. Second, it is considerably simple but shows a strong applicability in defining the monsoon timing. The onset and withdrawal dates of monsoon can be easily identified from the cumulative zonal wind series because the cumulative time series of a year exhibits one peak and valley pair. On the basis of these reasons, we recommend the use of this easy, objective, and effective method for determining the time of monsoon circulation.

Moreover, we examine the relationship between ENSO and the timing of the SCSSM. We find that a preceding El Niño (La Niña) can strengthen (weaken) the WNPSh and the Philippine Sea anticyclone, and prevent (favor) the monsoon flow from the Indian Ocean, thus leading to a late (an early) SCSSM onset. Additionally, we notice a significant negative correlation between the SCSSM withdrawal and ENSO, suggesting that El Niño (La Niña) can advance (delay) the monsoon withdrawal. The WNPSh during El Niño (La Niña) is located more southward (northward) and retreats earlier (later), thereby advancing (delaying) the withdrawal of the SCSSM.

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