Revisiting the ENSO–monsoonal rainfall relationship: new insights based on an objective determination of the Asian summer monsoon duration

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Abstract

Traditionally, the boreal summer monsoon season is regarded as a fixed period of June–September (JJAS). In fact, the monsoon commencement and termination are not fixed to the annual cycle, thus the monsoon duration exhibits remarkable variations. Based on the multivariable empirical orthogonal function analysis, the commencement, termination, and duration of the Asian summer monsoon (ASM) are objectively determined in this study. The ASM duration is shown to be closely linked to the sea surface temperature anomalies in the equatorial Pacific Ocean, which tends to be shorter during an El Niño and longer during a La Niña year. Through the anomalous Walker circulation and the equatorial Rossby wave response, a developing La Niña event is generally associated with advanced commencement and delayed termination, thus a longer ASM duration.

The importance of monsoon duration is illustrated further by revisiting the relationship between El Niño-southern oscillation (ENSO) and the monsoonal rainfall, which is the total rainfall within monsoon duration (from commencement to termination) rather than within JJAS. The relationship between the JJAS rainfall over South Asia and ENSO has exhibited remarkable interdecadal changes, which becomes weak since the 1980s and is recovered after the early 2000s. In sharp contrast, the linkage between the monsoonal rainfall over South Asia and ENSO remains significant and robust over the past four decades. Via attaching the rainfall during the transition periods (advanced commencement and delayed termination), the longer ASM duration during La Niña shall increase the total rainfall, which can reinforce the canonical ENSO-monsoonal rainfall relationship. The above results suggest that a reasonable definition of ASM duration may help us better understand the monsoon phenomenon and teleconnections.

1. Introduction

Through the seasonal reversal of low-level winds and the arrival and demise of the rainy season, the Asian monsoon exerts profound societal and economic impacts on half of the global population (Chen et al 2019, Wang et al 2021a). While the onset and withdrawal of the summer monsoon occur every year, the timing of these seasonal transitions is not fixed to the annual cycle. As such, the summer monsoon duration exhibits remarkable variations (Bombardi et al 2020, Chen et al 2022). In addition to the peak summer (June–September, JJAS), the changes in monsoon duration can also lead to severe droughts and floods as well as extreme events. For example, the extreme late monsoon onset over the South China Sea in 2018 (Liu and Zhu 2019) resulted in a record-breaking heat wave in southern China, with the highest air temperature anomaly exceeding 6 °C (Deng et al 2020, Zhang et al 2020). The monsoon withdrawal over the South China Sea in 2010 was delayed for about one month (Chen et al 2022), which led to the heaviest rainstorm on Hainan Island in the past 60 years and a direct economic loss of more than 3 billion China Yuan (Qiao et al 2015, Wang et al 2021b). Excessive monsoonal rainfall can either result from a more
vigorous rainfall intensity in peak summer (JJAS) or a longer monsoon duration (Noska and Misra 2016), which can exert remarkable influences on the rain-fed agriculture, water management, and human health (Bombardi et al 2020).

Due to the importance of the monsoon duration, numerous methods have been put forward to determine the monsoon onset and withdrawal (Bombardi et al 2020). These methods can be divided into two complementary perspectives: local-scale methods that focus on every grid point (e.g. Bombardi et al 2019) and regional-scale methods that are based on spatially averaged variables (Noska and Misra 2016, Liu and Zhu 2019, Vega et al 2020) or empirical orthogonal function (EOF) analysis (Yang et al 2021, Hu et al 2022). The local-scale methods can reveal the spatial progression of summer monsoon boundary, but may be contaminated by high-frequency noises (‘bogus’ monsoon onset; Noska and Misra 2016). The regional-scale methods mainly focus on the large-scale transition of atmospheric circulation and convection activities, which can be used to reveal the linkage among local-scale monsoon onsets (Hu et al 2022). To distinguish from local ‘monsoon onset and withdrawal’ over a specific domain, in this study the ‘monsoon commencement and termination’ is used when it comes to large-scale seasonal transitions. For example, based on the multivariable EOF (MV-EOF) analysis of daily outgoing longwave radiation (OLR) and low-level winds during April–June, Yang et al (2021) investigated the commencement of the large-scale Asian summer monsoon (ASM). The time when a steady transition of PC1 (principal component) occurred is regarded as the large-scale ASM commencement, which is highly correlated to the local monsoon onset over South Asia, Bay of Bengal, and South China Sea. The major motivation of this study is to extend this definition (Yang et al 2021) so that a unified monsoon termination and duration can also be determined.

As a prominent component of the ASM system, the South Asian summer monsoon (SASM) has been extensively studied for more than a century. The best-known measure of the SASM intensity is the area-averaged rainfall during JJAS, which accounts for about 80% of the annual precipitation (Kumar et al 1999, Walker and Bordoni 2016). The JJAS rainfall over the SASM region has been found to be negatively correlated with the sea surface temperature (SST) anomalies in the equatorial central-eastern Pacific, known as El Niño-Southern Oscillation (ENSO). However, the inverse relationship between ENSO and the SASM rainfall was broken down in the 1980s (Kumar et al 1999). Different hypotheses have been put forward to explain this phenomenon, including global warming (Kumar et al 1999), volcanic eruptions (Singh et al 2020), ENSO properties (Kumar et al 2006), Pacific Decadal Oscillation (Krishnamurthy and Krishnamurthy 2014), Indian Ocean dipole (Ashok et al 2001), and stochastic processes (Yun and Timmermann 2018). Interestingly, two recent studies reported that the linkage between ENSO and the SASM has been restored since the early-2000s (Yang and Huang 2021, Yu et al 2021). Yang and Huang (2021) argued that the tropical Atlantic SST anomalies are crucial, while Yu et al (2021) mainly emphasized the role of SST over the tropical Indian Ocean. However, these two studies are based on the total rainfall during JJAS, and a varying ASM duration has not been considered. As shown later, ENSO can modulate the monsoonal rainfall through the length of monsoon duration. The ASM duration is shrunk during El Niño events and expanded during La Niña events. Taking the monsoon duration into account, the linkage between ENSO and the SASM monsoonal rainfall has remained stable over the past four decades. This example demonstrates that it is necessary to define the duration of ASM, which has a more physical basis than a fixed monsoon season of JJAS.

2. Data and methods

The major datasets employed in this study include: (a) daily mean National Centers for Environmental Prediction-Department of Energy (NCEP-DOE) reanalysis data with a horizontal resolution of 2.5° × 2.5° (Kanamitsu et al 2002); (b) daily mean OLR data with a horizontal resolution of 2.5° × 2.5° (Liebmann and Smith 1996); (c) pentad mean Global Precipitation Climatology Project (GPCP) data with a horizontal resolution of 2.5° × 2.5° (Xie et al 2003); (d) monthly mean Hadley Centre Global Sea Ice and SST (HadISST) data with a horizontal resolution of 1° × 1° (Rayner et al 2003). All the above reanalysis and observational data cover the common analysis period of 1979–2020. Following Yang et al (2021) and Hu et al (2022), the MV-EOF analysis (Wilks 2019) is used to objectively determine the commencement, termination, and duration of the large-scale ASM. The statistical significance of linear regression, correlation, and composition is estimated by the two-sided Student’s t-test.

3. Results

3.1. Objective determination of the ASM duration

Tropical Asia is a typical monsoon region, which is dominated by low-level southwesterly winds in the boreal summer and northeasterly winds in the winter. Accompanying the annual reversal of near-surface winds, the convention center also exhibits seasonal migrations. Figure 1(a) shows the differences in OLR and low-level winds between summer (JJA) and winter (DJF). There appears enhanced convection over tropical Asia (from Arabian Sea to Philippine Sea) and suppressed convection over tropical South
Africa, Maritime Continent, and northern Australia. The differential latent heating between the Southern and Northern Hemispheres is the major driver of tropical ASM circulation, featured by southeast-erly winds in the Southern Hemisphere, strong cross-equatorial flow around Somali and Indonesia, and southwesterly winds in the Northern Hemisphere. In addition, the above circulation also feedbacks to the convection and rainfall by moisture transport and convergence.

To depict the seasonal march of the tropical ASM, the MV-EOF analysis is applied to the OLR and 850 hPa zonal winds (U850), which are frequently employed in depicting the seasonal transitions (Bombardi et al 2020, Chen et al 2022). This is because the tropical monsoon is dominated by active convection and zonal wind transitions, while the meridional wind transitions are relatively less important (Chen et al 2022). The daily data of OLR and U850 during 1979–2020 is employed, and the leap days are omitted. Namely, the time dimension of the data matrix is 365 × 42 = 15330. The analysis domain is (40°–140° E, 0°–30° N; rectangular in figure 1(b)) where the ASM is vigorous and the summer–winter contrasts are very large (figure 1(a)). Results are very similar when the analysis domain is slightly adjusted. The reference states of OLR and U850 are defined as the climatological annual mean in each grid point. Then, the two anomaly fields are normalized by the area-averaged standard deviation over the analysis domain, which are 35.5 W m⁻² for OLR and 5.2 m s⁻¹ for U850. To display the full horizontal winds and OLR in a larger domain, the convection and circulation associated with MV-EOF1 are obtained by regressing them onto the normalized PC1.

As shown in figure 1(b), the spatial structure of the first MV-EOF mode is very similar to the seasonal contrast of OLR and low-level winds (figure 1(a)), which indicates that this mode is capable to depict the annual cycle of ASM. It needs to mention that the changes revealed by these two relatively independent data (OLR and U850) are dynamically consistent. For example, the latent heating associated with the active convections shall excite equatorial Rossby wave to the west, which can enhance the westerly winds southwest of the convention center. Oppositely, the active convections are expected to overlay the low-level cyclonic vorticity where the Ekman pumping effect is strongest, which are expected to be located to the north of the strongest westerly winds. These dynamical consistencies imply that the first MV-EOF mode is not only a dominant statistical mode but also has physical meaning.

The corresponding PC1 during 1979–2020 and the climatological mean are shown in figure 2(a), which are generally positive during summer and negative during winter. The negative-to-positive transitions usually occur in May, which corresponds to the commencement of the large-scale ASM (e.g. Hu et al 2022). Meanwhile, the positive-to-negative transitions mainly appear in October, which reflect the termination of ASM. In most years, these transitions of PC1 are very clear, and the ASM commencement and termination dates are easy to be determined. However, in some years the PC1 fluctuates between positive and negative values. Generally, time smoothing (e.g. five-day running mean) or some subjective criteria (e.g. Yang et al 2021) are needed to fix the monsoon commencement and termination dates in these years. To objectively determine the ASM transitions, this study employs the cumulative series of PC1 following Bombardi et al (2019), which is defined as the summation of PC1 for day d and all previous days:

\[ \text{cumPC1} (d) = \sum_{i=1}^{d} \text{PC1} (i) \]

where cumPC1 (d) is the daily cumulative PC1 for day d of a particular year. The cumulative series of PC1 is shown in figure 2(b). Since the PC1 in the winter are negative, the cumulative PC1 in this period shows a decreasing trend. However, after the ASM commencement, the PC1 exhibits a firm transition from negative to positive, and the cumulative PC1 turns to an increasing trend. As such, the ‘valley’ of the cumulative PC1 can be regarded as the ASM commencement date. Similarly, the ‘peak’ of cumulative PC1 can be defined as the ASM termination date, which corresponds to the steady transition (positive-to-negative) of PC1. The time period between monsoon commencement and termination is regarded as the ASM duration.

The ASM commencement and termination dates during 1979–2020 are shown in figure 2(c), and the year-calendar evolution of PC1 is also shown for a comparison. As mentioned above, the ASM commencement and termination dates are defined as the firm transitions of PC1. The ASM commencement generally occurs in May, with the average commencement date of 11 May and a standard deviation of 8 d. Meanwhile, the ASM termination generally occurs in October, with the mean termination date of 13 October and a standard deviation of 9 d. This is consistent with the transitions of PC1, which mainly appears in May and October (figure 2(a)). Moreover, the fidelity of monsoon commencement and termination dates is further examined in figures S1 and S2, in which the composited evolution of OLR and low-level winds during these monsoon transitions are presented. The ASM commencement is featured by the development and northward advance of vigorous convection and monsoonal westerly winds, which marks the large-scale adjustment of circulation and convection from the winter-type to the summer-type (figure S1). Approximate opposite features accompanying the ASM termination are evident in figure S2.
Taken the monsoon commencement and termination together, the ASM duration can be determined. The average duration of ASM is 156 d (about five months from mid-May to mid-October), with a standard deviation of 12.6 d. The longest ASM duration is 194 d (more than six months), while the shortest monsoon duration is 125 d (about four months). These results indicate that the ASM duration exhibits large variations, and a fixed monsoon season of JJAS may miss some important information related to the monsoon duration.

3.2. Revisiting the ENSO–monsoonal rainfall relationship

While many studies have analyzed the monsoon onset and commencement, fewer studies focused on the monsoon withdrawal or termination (Bombardi et al 2020, Chen et al 2022; and references therein). Even fewer studies have focused on the duration of summer monsoon. We noticed that the longest ASM duration occurred in 1999 which is a La Niña year, while the shortest monsoon duration occurred in 1987 which is an El Niño year. To investigate the linkage of ASM
duration and ENSO, figure 3(a) shows the evolution of the correlations between monsoon duration and the equatorial SST anomalies. Corresponding to a longer ASM duration, there appears significant cold SST anomalies in the central-eastern Pacific and warm SST anomalies in the western Pacific. Such SST anomalies are evident from late spring to the following winter, which resembles development of a La Niña event. Figure 3(b) further shows the spatial pattern of correlation between the ASM duration and the SST anomalies during JJAS, which displays a typical structure of La Niña. Associated with a longer duration of ASM, there tends to have significantly negative SST anomalies in the equatorial central-eastern Pacific and significantly positive SST anomalies in the western Pacific, with the latter extending in a horseshoe-like structure to the subtropical South and North Pacific. We further examine the composited evolution of PC1 during the El Niño and La Niña years as shown in figure 3(c). Here, the El Niño (La Niña) events are identified as JJAS Niño3 index greater (less) than 0.5 °C (−0.5 °C). Compared to the El Niño years, the ASM commencement is earlier while the termination is delayed in the La Niña years. Therefore, the monsoon duration tends to be shrunk during warm ENSO phases and be expanded during cold ENSO phases. It should be noted that such conclusions are robust and not sensitive to other ENSO indices such as Niño3.4 index (figure S3).

Figures 3(d) and (e) show the ENSO composited (La Niña minus El Niño) OLR, winds at 850 hPa, and velocity potential at 200 hPa in May and October, which are the transition periods of the ASM (figure 2). Accompanying a developing La Niña, the east-west SST gradient over the Pacific Ocean (figures 3(a) and (b)) drives the anomalous Walker circulation, with low-level divergence, descending motion, and upper-level convergence over the equatorial central-eastern Pacific. In addition, anomalous upper-level divergence and ascending motion appear over the Maritime Continent and tropical ASM region. These ascending motions shall enhance the convection and rainfall over the tropical ASM region during the transition periods. Moreover, the anomalous warm SST and ascending motion over the Maritime Continent and western North Pacific shall increase the rainfall therein, which can act as a heat source that drives the atmospheric circulation. The anomalous cyclone circulation and westerly winds over the North Indian Ocean (figures 3(d) and (e)) can be interpreted as the equatorial Rossby wave response (Matsuno 1966, Gill 1980) to the heating forcing (figure S4). The difference in the circulation anomalies during May and October may be attributed to the changes in atmospheric mean flow and moisture background (Wang and Xie 1996, Hoskins and Wang 2006, Webster 2020). These circulation anomalies can reinforce the increased rainfall anomalies over the tropical ASM region via moisture transport and Ekman pumping effect. In summary, through anomalous Walker circulation and equatorial Rossby wave response, the developing La Niña can enhance the low-level westerly winds and convection activities during the transition periods over the tropical ASM region. Such anomalous westerly winds and enhanced convection are favorable for advanced commencement, delayed termination, and longer ASM duration. The opposite also holds true for a developing El Niño.
Conventionally the summer monsoon season is regarded as JJAS, and the rainfall within JJAS is considered to be monsoonal rainfall (e.g. Kumar et al. 1999). However, as shown in figure 3(c), the ASM duration is not fixed and exhibits remarkable variations. As such, a reasonable definition of monsoonal rainfall should take into account the monsoon duration. Namely, only the rainfall that occurs within the monsoon duration (from monsoon commencement to termination) should be recognized as the monsoonal rainfall. Figures 4(a) and (b) show the composited differences between the JJAS La Niña and El Niño in total rainfall within JJAS and the ASM duration, respectively. Corresponding to a summer La Niña, significantly increased JJAS rainfall mainly occurs in the Maritime Continent, and the rainfall anomalies are generally weak and insignificant in the ASM region (figure 4(a)). However, when the monsoon duration is considered, the relationship between ENSO and the monsoonal rainfall in the ASM region becomes much stronger (figure 4(b)). Specifically, corresponding to a summer La Niña, there appears significantly increased monsoonal rainfall in the Arabian Sea, India subcontinent, southern Bay of Bengal, Indochina Peninsula, and South China Sea. It should be noted that these results are robust, which are not sensitive to the dataset (figure S5) or statistical method (figure S6).

We further investigated the rainfall in the SASM region (rectangular in figures 4(a) and (b)) where many studies have focused (see the Introduction) with a very large population. Figure 4(c) shows the normalized time series of the JJAS Niño3 index and the total rainfall in the SASM region during JJAS and the monsoon duration, respectively. The result indicates that ENSO is more closely linked to the monsoonal rainfall ($r = -0.61$) than the JJAS rainfall ($r = -0.36$). Figure 4(d) shows the 15 year running correlations between the Niño3 index and two types of total rainfall. The relationship between ENSO and the JJAS rainfall is rather weak since the 1980s, which is consistent with Kumar et al. (1999). Meanwhile, their relationship gets better in recent years, which is again consistent with the recent studies (Yang and Huang 2021, Yu et al. 2021). However, when the monsoon duration is considered, the relationship between ENSO and the monsoonal rainfall remains stable and robust over the past four decades. Again, this result is robust, which is not sensitive to dataset (figure S7), the ENSO indices (figure S8), and statistical methods like wavelet coherence (figures S9 and S10). Notice that the relationship between the ASM duration and ENSO is also robust and significant over the past 40 years (figure S11). The individual role of monsoon commencement (termination) has also been examined by calculating the total rainfall from the
ASM commencement to September (from June to the ASM termination) as shown in figure 4(d). The result indicates that the relationship between ENSO and the total rainfall (green and purple curves) is weaker than the monsoonal rainfall (blue curve) if only considering the monsoon commencement or termination, but still stronger than the JJAS rainfall (red curve). Therefore, both the monsoon commencement and termination are suggested to include in depicting the ASM duration and the monsoonal rainfall.

The possible mechanism why considering the ASM duration can induce a more robust and stable ENSO-monsoonal rainfall relationship is explained as follows. Since the transitions of the ASM generally occur in mid-May and mid-October, the total rainfall within ASM duration contains two parts: the rainfall within JJAS, and the rainfall associated with ASM commencement and termination. The similar variation of the red and blue curves in figure 4(d) can be attributed to the rainfall within JJAS, which may be associated with the SST anomalies in the tropical Indian Ocean (Yu et al 2021) and the Atlantic Ocean (Yang and Huang 2021). And the difference between the red and blue curves in figure 4(d) is attributed to the rainfall associated with the ASM duration. Corresponding to the developing La Niña, the convection and rainfall are enhanced over the tropical ASM region during the transition periods (figures 3(d) and (e)), and the duration of ASM is also expanded (figure 3(c)). As such, the expanded ASM duration can attach the rainfall during the transition periods into the monsoonal rainfall as well. Specifically speaking, the advanced ASM commencement shall include the increased rainfall during early May and late April, and the delayed ASM termination shall include the increased rainfall during late October, thus contributing to the increased total rainfall during the La Niña years. In contrast, the shrunk ASM duration in the El Niño years is favorable for the decreased total rainfall and is more prone to drought. As such, after considering the variations of the ASM duration, the increased total rainfall during La Niña and decreased total rainfall during El Niño can reinforce the canonical ENSO-JJAS rainfall relationship (e.g. Kumar et al 1999), thus showing a stronger and more robust ENSO-monsoonal rainfall linkage.

4. Conclusion and discussion

Based on the MV-EOF analysis of daily OLR and U850, the commencement, termination, and duration of tropical ASM are objectively determined in this study. The first MV-EOF mode can well reflect the winter-summer contrast of convection and circulation around the ASM region. The firm transitions of PC1 are regarded as the monsoon commencement and termination, which is identified by the cumulative series of PC1. The ASM duration is defined as the time period from the monsoon commencement to termination. The ASM commencement, termination,
and duration obtained by this method do not need any time smoothing or subjective criteria, which is more objective.

The relationship between the monsoonal rainfall and ENSO is further examined after considering the monsoon duration. The result indicates that the ASM duration tends to be longer during the La Niña years and to be shorter during the El Niño years. ENSO may modulate the ASM duration via the anomalous Walker circulation and the equatorial Rossby wave response. Thus, ENSO may affect the ASM rainfall (i.e. total rainfall from the monsoon commencement to termination) via changing the monsoon duration. Previous studies reported that the relationship between ENSO and the JJAS rainfall in the SASM region exhibits remarkable interdecadal changes (Yang and Huang 2021, Yu et al 2021). Our results prove that the relationship between the monsoonal rainfall and ENSO remains significant over the past four decades if using the monsoon duration instead of fixed monsoon season (JJAS).

As mentioned in the Introduction, there are two perspectives in investigating seasonal transitions. The ASM commencement and termination derived in this study can provide a first-order view of the broad tropical ASM, namely, the coherent interannual variations of the monsoon sub-systems. The large-scale ASM commencement and termination certainly cannot replace the local monsoon onset and withdrawal, but rather a supplement to the local perspective. While Xavier et al (2007) also used the monsoon duration to explain the changing relationship between ENSO and the monsoonal rainfall, they mainly focused on the India subcontinent. In comparison, this study focused on a much larger domain of the tropical ASM region, extending from the Arabian Sea to the South China Sea. Indeed, the stronger relationship between the monsoonal rainfall and ENSO is not confined to the SASM region as shown in figure 4(c), but also in Indochina Peninsula (figure S12) and the whole tropical ASM region (figure S13). In addition, Xavier et al (2007) mainly focused on the changing relationship between ENSO and India rainfall around the 1980s. This study pays more attention on the recent epoch and especially the interdecadal change of early-2000s.

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Data availability statement

The NCEP-DOE reanalysis data is available at ftp://ftp.cdc.noaa.gov/Datasets/ncep.reanalysis2.dailyavgs/.

The OLR data is available at ftp://ftp.cdc.noaa.gov/Datasets/interp_OLR/.

The GPCP data is available at ftp://ftp.cpc.ncep.noaa.gov/precip/GPCP_PEN/.

The HadISST data is available at www.metoffice.gov.uk/hadobs/hadisst/.
