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The variability of the Southeast Asian summer monsoon

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ABSTRACT: In this article, we focus on the analysis of the climate variability of the Southeastern Asian Summer Monsoon (SEAM) region encompassing Myanmar, Thailand, Cambodia, Vietnam, Laos and parts of southern China. This region is climatologically found to have one of the longest wet seasons in the Asian monsoon region (of nearly 160 d) and also exhibits one of the strongest interannual variations in the length of the monsoon (wet) season. The interannual variations of the length of the SEAM are characterized by corresponding variations in the onset and demise pentad dates of the wet season, with the former dominating slightly over the latter except over Myanmar. Our study reveals that the pentad of late onset of SEAM is characterized by anomalous increase in remote moisture source from Bay of Bengal and Arabian Sea while a substantial decrease of moisture source from the near Andaman Sea and Gulfs of Martaban and Thailand. Furthermore, anomalously strong June–August Somali Jet is found to be associated with earlier than normal onset of the SEAM. Similarly, the pentad of late demise of the SEAM features excess moisture source from the South China Sea associated with a slow eastward withdrawal of the north Pacific subtropical high.
We suggest on the basis of the findings of this study that careful monitoring of the onset the SEAM season will provide important information on the evolution of an ongoing SEAM. Likewise observing low level winds over the northern equatorial Indian Ocean, Bay of Bengal, Gulfs of Martaban and Thailand and South China Sea could be very useful in understanding the seasonal variability of the SEAM. Finally, monitoring of the demise would be equally helpful in characterizing the variation of the concluded SEAM as the length of the wet season seems to be a very robust climate feature of the region.

KEY WORDS Monsoon onset; Monsoon demise; length of wet season; interannual variation

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1. Introduction

The Asian monsoon region, while a planetary scale phenomenon, has considerable heterogeneity within. The Asian monsoon is broadly classified as part of two subsystems namely the Indian summer monsoon and East Asian summer monsoon (Ding and Chang, 2005 and references therein). There are, however, other studies which classify the Asian summer monsoon into three subsystems (e.g. Wang and LinHo, 2002). They divided the Asian monsoon into Indian, East Asian and west north Pacific summer monsoons based on a unique metric called the relative pentad mean that measures the summer–winter rainfall contrast. Nevertheless, it is quite apparent from the review of recent literature that while considerable attention has been paid on studying the Indian and the East Asian summer monsoon (Wang, 2006 and references therein) there are but few studies that hone in on the southeast countries that include Myanmar, Thailand, Cambodia, Laos and Vietnam (Kripalani and Kulkarni, 1997, 1998; Sen Roy and Kaur, 2000). In this study, we closely examine a feature of the Asian summer monsoon that seems to stand out in these southeast Asian countries, namely the significant interannual variability of the length of the wet season. Earlier studies have documented the progression of the onset of the Asian monsoon with the earliest onset occurring first in the eastern Bay of Bengal and the Indochina Peninsula in the middle of May followed by that over South China Sea in late May and finally the Indian monsoon onset in early June (Tanaka, 1994; Webster *et al*., 1998; Chang *et al*., 2004; Qian and Yang, 2000).

There are a number of studies that indicate the importance of soil moisture in influencing the atmospheric variability in early summer over the Asian monsoon region (Webster *et al*., 1998 and references therein). Delworth and Manabe (1988, 1989) using a rather (now) archaic land surface model (Bucket model; Manabe, 1969) differentiated humid from dry monsoon regions based on the ratio of precipitation over potential evapotranspiration. They termed India and northeast Asia to be relatively dry monsoon regions and southeast Asia region to be a humid monsoon area. They showed from their modeling study that autocorrelation of soil moisture anomaly was small in humid monsoons relative to the dry monsoon regions. Similarly Koster *et al*. (2005) more recently

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showed using multiple and more modern general circulation models that impact of soil moisture anomaly on precipitation is significant in relatively dry monsoon regions but not in the humid monsoon regions.

In a recent study, Wang and Chang (2012) highlighted the interaction of the orographic precipitation and the monsoon circulation in the southeast Asian region. They found through model sensitivity tests that the monsoon onset in the Indo-China peninsula is a manifestation of the local wind–terrain–precipitation interaction, which is in contrast to the Indian monsoon onset that is more governed by the large scale. In the following section, we briefly describe the datasets used in the study followed by a discussion of the methodology. In Section 4, we present the results with summary and concluding remarks in Section 5.

2. Datasets

This study uses the daily rainfall from the APHRODITE project (Yatagai *et al*., 2012). This is a gridded dataset available daily over the entire Asian monsoon region for the period from 1951 to 2007. It uses over 12 000 rain gauge observations over the Asian continent to produce this gridded rainfall analysis. The rain gauge data is quality controlled and the ratio of observed precipitation to climatology is interpolated to the analysis grid. Weighting is performed based on elevation to account for orographic effects. The resulting gridded ratios are multiplied by climatology to obtain precipitation amounts in mm day^{-1}.

In addition we utilize the 6-h global winds, temperature and humidity for the entire atmospheric column from the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR; Saha *et al*., 2010) for conducting the back trajectory analysis. They are available at a grid resolution of approximately 40 km.

3. Methodology

The length of the Southeastern Asian Summer Monsoon (SEAM) season is determined objectively following Liebmann *et al*. (2007) using their definition of the cumulative anomalous rainfall accumulation (C'_m) defined for every grid point as:

$$C'_m = \sum_{n=1}^{N\text{DAYS}} \left\{ P_m(n) - \overline{P}_m \right\} \tag{1}$$

where $P_m(n)$ is daily rainfall on day n and mth year, n is day number starting on day 1, which is January 1 and ending on day N, which is December 31 and $\overline{P}$ is annual average of the daily rainfall, the length of SEAM is defined as the period with the longest positive slope of the time series of C'_m from (1). This definition especially for the monsoon regions reduces to the fact that the beginning of the rainy season corresponds to the period when the anomalous accumulation is above the annual mean and the demise corresponds to the time when the anomalous accumulation is maximum. Once the start, demise and length of the SEAM season are determined objectively in this manner, their climatological values and anomalies can be ascertained simply (Misra and DiNapoli, 2012).

To determine the evaporative sources of the SEAM rainfall, we calculate the Quasi-Isentropic Back Trajectories (QIBT) following Dirmeyer and Brubaker (1999). To compute this back trajectory it uses winds and temperature (at several pressure levels), surface evaporation and precipitable water from CFSR and rainfall data from APHRODITE. At each CFSR grid location (in the square box outlined in Figure 2) where rain is observed, parcels are initialized at a random humidity-weighted level with moisture content equal to the amount of rainfall at the initialization integrated over a 5-d period. The parcels are then advected isentropically back in time with the analyzed wind field from CFSR. In the event that the parcel drops below the land surface, it is raised to the surface level so that the trajectory never intersects the ground. At each hourly time step of the QIBT, each parcel loses a fraction of its moisture equal to the ratio of the surface evaporation rate divided by the total column integrated precipitable water at the parcel's location. This process continues for up to 15 d, or until the parcel loses more than 90% of its original moisture content. At each grid point, the total amount of moisture removed from the parcels is summed to obtain the moisture source. This method does not account for phase changes along the parcel trajectory (e.g. condensation) or intervening moisture sinks along the trajectory path (e.g. remote precipitation events). QIBT has been extensively used for determining the evaporative sources in many of the prior studies (Dirmeyer and Brubaker, 1999; Reale *et al*., 2001; Chan and Misra, 2010; Misra *et al*., 2012). Obviously, the results of this back trajectory analysis is critically dependent on the reanalysis used. However, Misra *et al*. (2012) showed in their comparison of the evaporative sources of the central Indian monsoon that CFSR and modern era retrospective reanalysis (MERRA; Rienecker *et al*., 2011) were more similar to each other than the National Centers for Environmental Prediction-Department of Energy reanalysis (R2; Kanamitsu *et al*., 2002).

4. Results

4.1. Climatology

The climatology of the length of the monsoon season in Figure 1 clearly shows that SEAM has one the longest wet seasons in the Asian region. In the SEAM region, this length ranges from 120 to 160 d in stark contrast to the Indian monsoon (outside of the northeast region), which ranges from 80 (over northwest and southeast India) to 120 d (over central and southwest India). The corresponding standard deviation of this length of the wet season is shown in Figure 2(a) from which it is apparent that the variability is comparatively larger

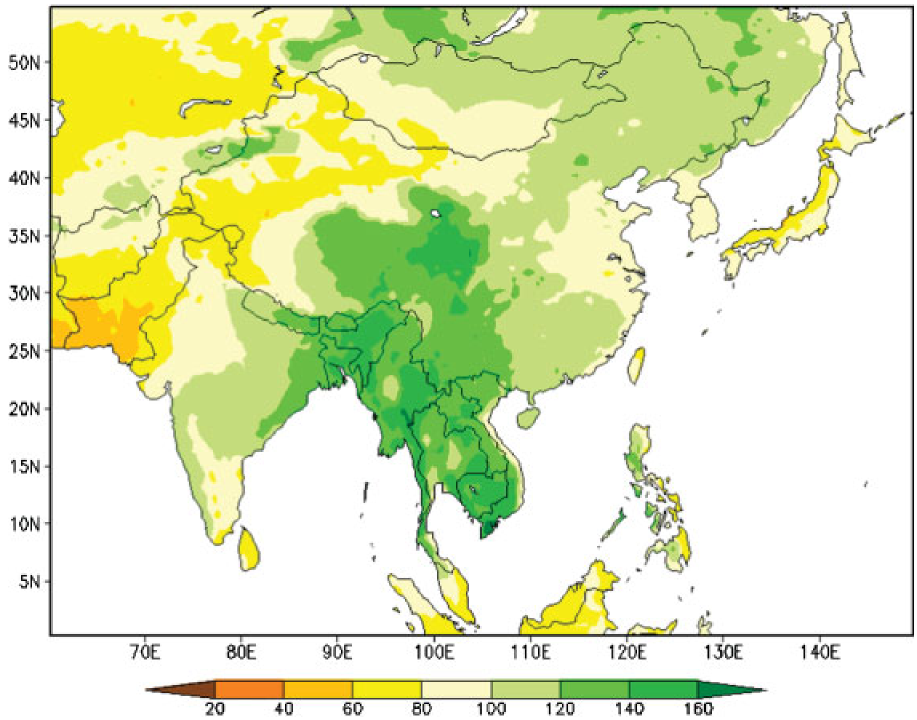

Figure 1. The climatology of the length of the summer monsoon season (in days).

over the SEAM region. Interestingly, Myanmar displays the largest interannual variation in the SEAM. This is characterized by comparable variations in the onset date and slightly higher variations in the demise date of the monsoon over Myanmar (Figure 2(b) and (c)). In the rest of SEAM, the variations of the onset date seem to be larger than those of the demise date. On the other hand, the variability of the length of the Indian monsoon season is relatively much shorter, with southeastern India exhibiting the most variations.

The climatological evaporative source for the wet season of the SEAM region is shown in Figure 3(a). The largest evaporative sources for the rainy season in the SEAM region seems to come from the immediate vicinity of the Andaman Sea, Gulfs of Martaban and Thailand and local land based evaporation followed by the western reaches of the Bay of Bengal, the eastern Arabian Sea-western Indian Ocean and relatively less but significant evaporative source from South China Sea (Figure 3(a)). Similarly, the Andaman Sea and Gulfs of Martaban and Thailand are shown to be the largest climatological evaporative sources for the onset pentad of the SEAM wet season (Figure 3(b)), with substantial contributions from local land-based evaporation and extending to far western reaches of the Bay of Bengal with significantly far less contributions from the Arabian Sea and western Indian Ocean. Figure 3(c) shows that climatologically during the demise pentad of the wet season the local land-based evaporation is the largest contributor followed by that from the Bay of Bengal and South China Sea.

Associated with Figure 3 are the climatological wind flow patterns at 850 hPa for the onset and demise pentads of the wet season shown in Figure 4(a) and (b), respectively. Here, it is seen that at the time of the onset (Figure 4(a)), the west-southwesterly flow is well established over the Bay of Bengal, Andaman Sea and Gulfs of Martaban and Thailand, while the low-level flow is comparatively much weaker over the Arabian Sea. This flow pattern is consistent with evaporative sources from the Bay of Bengal and Andaman Sea contributing more significantly to rainfall over SEAM during the onset pentad (Figure 3(b)). Similarly, at the time of the demise of the wet season the 850 hPa flow pattern (Figure 4(b)) suggests a strong southwesterly flow across the northern equatorial Indian Ocean (but south of 10°N) with relatively weaker winds over the Bay of Bengal, Andaman Sea and Gulfs of Martaban and Thailand. This is again consistent with the reduced contribution of the neighboring oceanic evaporative sources to rainfall during the demise pentad of the SEAM season (Figure 3(c)).

4.2. Interannual variability

Figure 5(a) and (b) shows the correlation of the onset (demise) date of the SEAM with the length of the season, respectively. A negative correlation in Figure 5(a) would mean that early onset is associated with longer length of the SEAM season. Similarly in Figure 5(b) a positive correlation would mean that late demise is associated with longer length of the SEAM season. In both Figure 5(a) and (b), it is quite apparent that longer lengths of SEAM are usually associated with early onset and (or) late demise of the season. It should be however noted that the correlation over western and central Thailand between the variations of the demise date and the length of the season

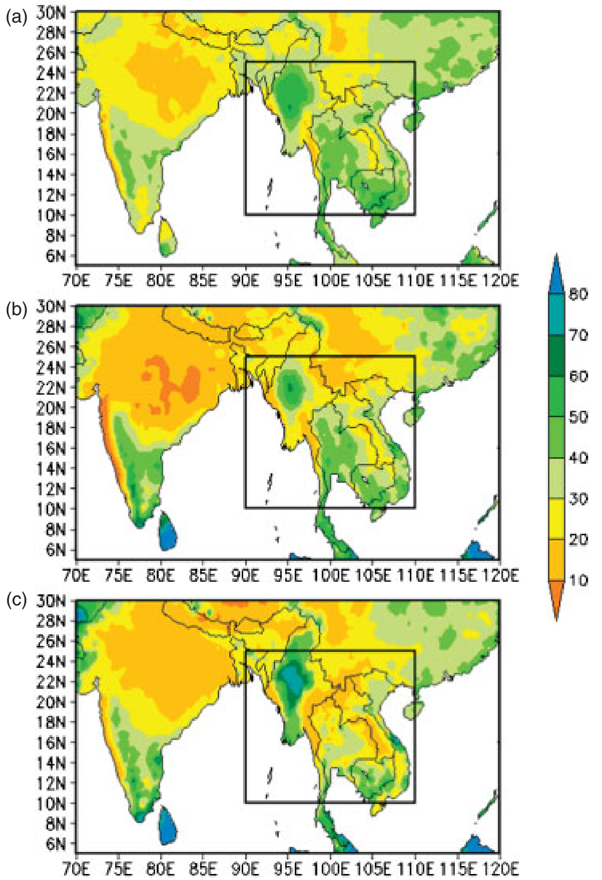

Figure 2. The standard deviation of the (a) length, (b) start date and (c) end date of the summer monsoon season. The outlined box (southeastern Asia) is the region for which evaporative (or moisture) sources will be diagnosed.

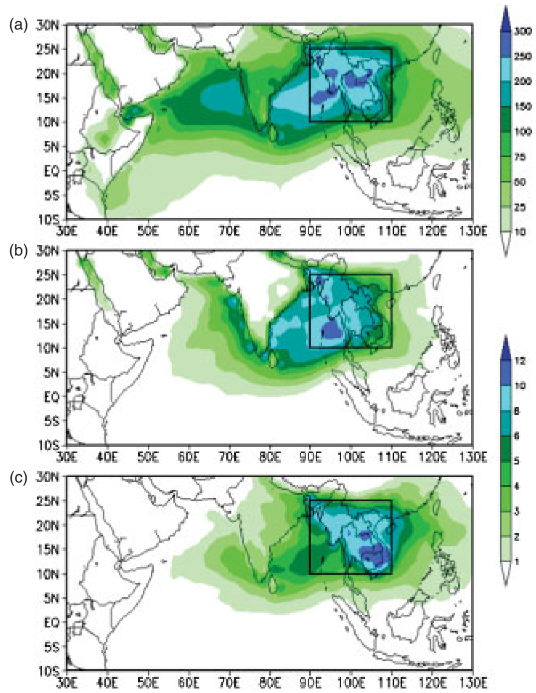

Figure 3. The climatology of the evaporative sources for the (a) summer monsoon season, (b) onset pentad and (c) demise pentad over the Southeastern Asian Monsoon region.

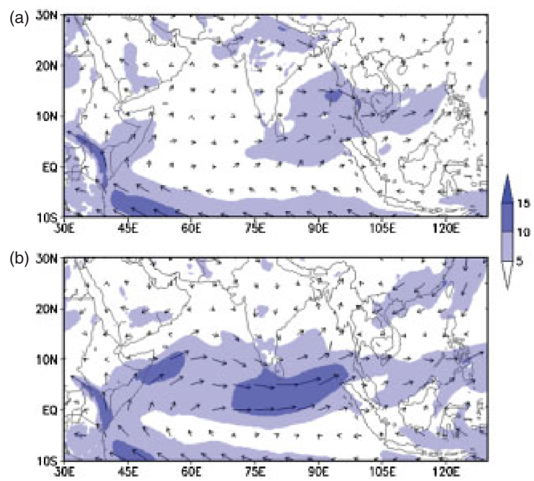

Figure 4. Climatological 850 hPa wind flow pattern for climatological (a) onset and (b) demise pentad of the SEAM.

is weaker than in the rest of southeast Asia (Figure 5(b)). On the other hand, it is observed that the onset date of the SEAM is rather weakly correlated with the rain rate in the wet season (except over southern Myanmar; Figure 6(a)) compared to the correlations between the demise date and the seasonal rain rate in Figure 6(b). In Figure 6(a) and (b), a negative (positive) correlation would mean early onset (late demise) is associated with heavier average rain rate of the SEAM season. It is apparent from Figure 6(b) that the seasonal rain rate variation of the SEAM season is more closely and strongly associated with the variation of the demise date of the season, especially over central and southern Thailand, Laos, Cambodia, Vietnam and northern Myanmar.

Figure 7 shows the correlations of the variations of the onset with the demise of the SEAM season. Besides the region over central Myanmar and south Vietnam, the rest of the SEAM shows a positive correlation. This positive correlation suggests that early onset of the wet season is associated with early demise. Figures 5 and 7 reveal that with the exception of probably central Myanmar and south Vietnam early onset with early demise or late onset with late demise or early onset with normal demise or normal onset with late demise in these regions could still cause an anomalous lengthening of the wet season. It may be mentioned that the onset, demise and the length of the SEAM did not have a consistent relationship with the seasonal activity of the tropical cyclones in the region (not shown)

4.3. Composite analysis

Figure 8(a) and (b) shows the composite evaporative sources for the five shortest and longest wet seasons

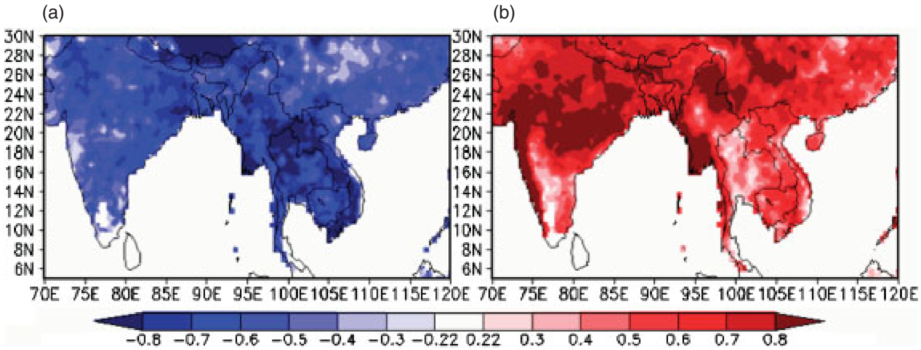

Figure 5. The correlation of the (a) onset and (b) demise of the wet season with the length of the wet season over the SEAM region. Statistically significant correlations at 90% confidence interval according to t-test are shown.

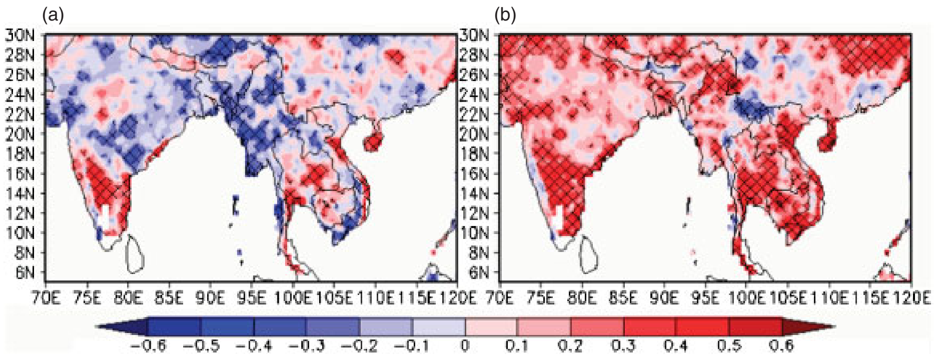

Figure 6. The correlation of (a) onset date and (b) demise date with the rain rate of the wet season over the SEAM region. Statistically significant correlations at 90% confidence interval according to t-test are hatched.

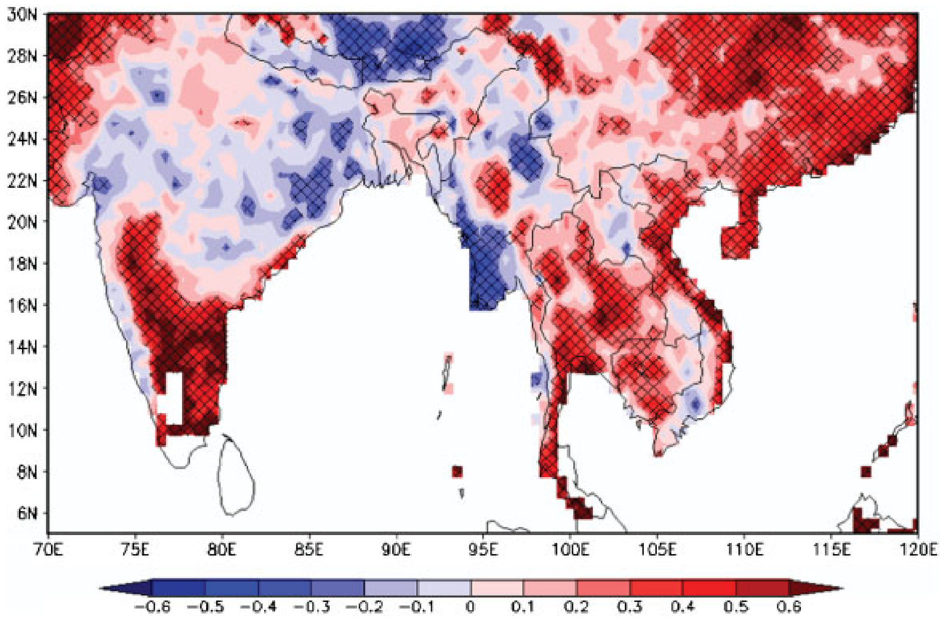

Figure 7. The correlation of the onset with the demise date of the SEAM season. Statistically significant correlations at 90% confidence interval according to t-test are hatched.

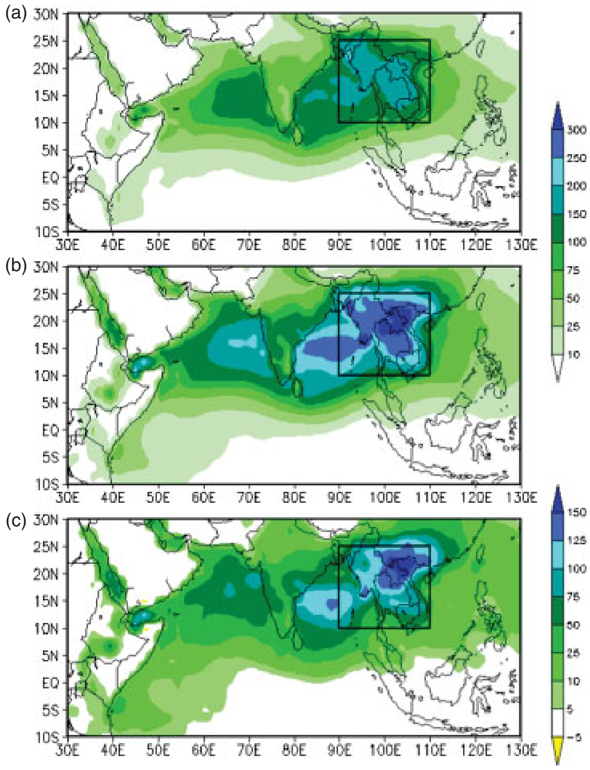

Figure 8. Composite of the evaporative sources for (a) short and (b) long summer monsoon season and (c) b–a over southeastern Asia.

over the period 1979–2007, respectively. In a long wet season, there is an increase in both the oceanic and local land-based evaporative sources (Figure 8(b) and (c)) relative to the short wet season (Figure 8(a) and (c)). There is however larger increase in the land-based evaporative source than the neighboring oceanic evaporative source over the Bay of Bengal during long SEAM seasons relative to the short wet seasons. In Table I, we show the distribution of the frequency of anomalous onset and demise dates associated with anomalous length of the wet season of SEAM. For the most extreme short wet seasons (fifth percentile), the table reveals that it is characterized by a late onset in 100% of the cases with 33% (67%) probability of early (normal) demise. Similarly for the most extreme long wet season (fifth percentile), it is shown that 80% (20%) of such seasons feature early (normal) onset and 60% (40%) feature late (normal) demise. Figure 9(a) and (b) shows the composite evaporative sources for pentads of the anomalous early and late onset of the SEAM season with their differences in Figure 9(c), respectively. In comparing these three figures, it is clearly seen that late onset of SEAM is characterized by a decrease of evaporative sources from the Andaman Sea and the Gulfs of Martaban and Thailand and an increase in evaporative sources from Bay of Bengal and Arabian Sea. In other words, the oceanic evaporative sources are more remote during late onset pentad. In addition, the local land-based evaporative source is also reduced during late onset. Similarly, the composite evaporative sources for early and late demise and their difference are shown in Figure 9(d)–(f), respectively. These figures indicate that during late demise the land-based evaporative source increases considerably with comparable increase in the evaporative source from South China Sea as well.

The anomalous 850 hPa flow patterns for the early (Figure 10(a)) and late onset (Figure 10(b)) pentads and for early (Figure 10(d)) and late (Figure 10(e)) demise pentads are shown to be consistent with the corresponding anomalous evaporative sources displayed in Figure 9. In early onset pentads, the low level flow is stronger than climatology over the Bay of Bengal and in the Gulfs of Martaban and Thailand (Figure 10(a)) while it is weaker than climatology in these regions during late onset pentads (Figure 10(b) and (c)). Likewise during early demise pentads, the low-level flow over SEAM is weaker than climatology and the anomalous flow over South China Sea is southwesterly (Figure 10(d)). In contrast during late demise pentads, the 850 hPa flow over SEAM is stronger than climatology, which enhances the evaporation and the flow over South China Sea is northeasterly.

4.4. Relation with Somali jet

Halpern and Woiceshyn (2001) suggested a relationship between the variations of the Somali jet and the rainfall along west coast of India. They found that stronger

Table I. The percentage of early, late and normal onset of SEAM for anomalous length of SEAM.

Percentile of the anomalous length of SEAM	Percentage of onset date contributing to the anomalous length of SEAM			Percentage of demise date contributing to the anomalous length of SEAM		
	Early (%)	Normal (%)	Late (%)	Early (%)	Normal (%)	Late (%)
The fifth percentile of the shortest SEAM season (three seasons)	0	0	100	33	67	0
The tenth percentile of the shortest SEAM season (five seasons)	20	20	60	60	40	0
The fifth percentile of the longest SEAM season (three seasons)	80	20	0	0	40	60
The tenth percentile of the longest SEAM season (five seasons)	100	0	0	0	33	67

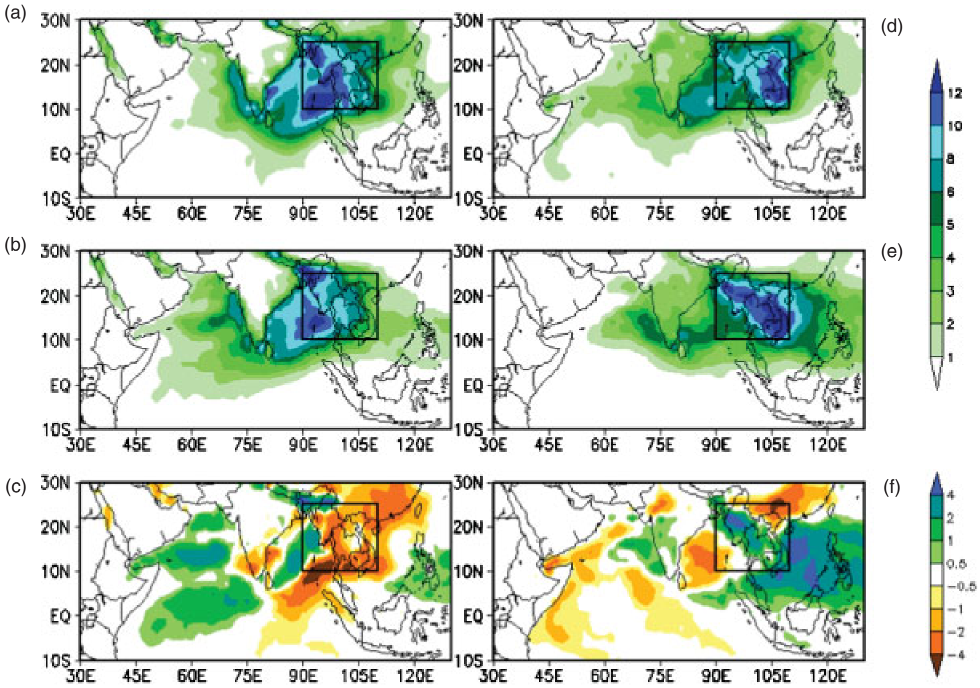

Figure 9. Composite of the evaporative sources for pentads of (a) early onset, (b) late onset, (c) b−a, (d) early demise and (e) late demise (f) e−d of the Southeastern Asian Monsoon season

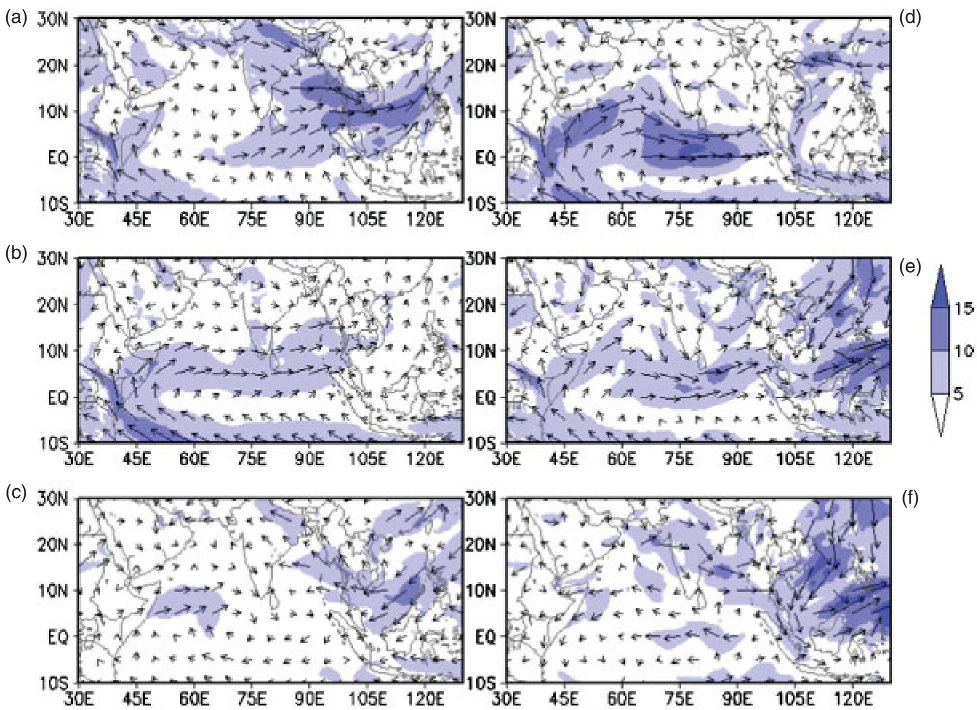

Figure 10. Composite of the 850 hPa winds for (a) early onset, (b) late onset, (c) b−a, (d) early demise and (e) late demise (f) e−d of the Southeastern Asian Monsoon season. The unit of wind speed is ms^{-1}.

(weaker) monthly mean intensity of the Somali jet was associated with above (below) normal rainfall along the west coast of India. In a similar vein, we examined the relationship of the SEAM features with the Somali jet (Table II). Following Halpern and Woiceshyn (2001) and Meijin *et al*. (2008), we define the onset of the Somali jet as the first 2-d interval of three consecutive 2-d intervals when the maximum wind speed is above $12\,ms^{-1}$ in the western Arabian Sea domain of 35°E–60°E and 15°S–15°N. Table II shows that variability of the onset

Table II. The correlation of the Somali Jet with the features of the Southeast Asian Monsoon. Figures in bold pass statistical significance according to t-test with 90% confidence interval.

	Length of SEAM	Onset of SEAM	Demise of SEAM
Onset of Somali Jet	−0.231	0.335	0.089
JJA mean wind in western Arabian Sea	0.173	−0.341	−0.169

of the Somali jet is positively and in a statistically significant manner correlated to the onset of the SEAM. This would suggest that a late onset of Somali jet is associated with late onset of SEAM. This results in a shortened length of SEAM (Table I), albeit it does not pass statistical significance test. However, the variability of the onset of the Somali jet does not have as robust of an influence on the demise of SEAM. Similarly the JJA seasonal mean variation of the 850 hPa winds in the western Arabian Sea is negatively correlated with onset of SEAM. This indicates that a strong seasonal JJA Somali jet is associated with early onset of SEAM. It may be noted that we found no significant relationship of the onset, demise and length of SEAM with the variations in the tropical easterly jet in the upper troposphere (not shown).

5. Summary and conclusions

The variation of the length of the wet season is a robust feature of the SEAM. The region as a whole stands out with the longest wet season in the entire Asian monsoon region. A long SEAM season is likely associated with early onset and or late demise of the season. There is considerable local heterogeneity in the variations of the length of the wet season with Myanmar showing larger variability than the rest of the SEAM. Furthermore, the co-variation of the periods of onset with the demise of the wet season is of opposite sign in southern Myanmar and southern Vietnam relative to the rest of SEAM. The variability of the onset and demise of the SEAM season can independently of each other modulate the length of the wet season or the dominance of the variation in either the onset or the demise of the wet season can also modulate the length of the wet season, which is most likely the case over central Myanmar, Thailand, Cambodia and northern Vietnam. In southern Myanmar and southern Vietnam early (late) onsets are generally associated with late (early) demise of the wet season. Early onsets of the SEAM are characterized by enhanced evaporative sources from the Andaman Sea and Gulfs of Martaban and Thailand while late onsets features enhancement from the more remote Bay of Bengal and Arabian Sea. The early onset of the SEAM is also characterized by a stronger than normal JJA seasonal mean Somali jet. The period of late demise of the SEAM season on the other hand shows enhancement of evaporative source from the local land based evaporation and from South China Sea relative to the period of early demise seasons. The 850 hPa flow pattern seems to be consistent with the anomalous evaporative sources that characterize the variations of the onset and demise of the SEAM season. The low level flow enhances or diminishes the climatological flow in the regions where evaporative sources are attributed to be significant to the variation of either the onset or demise of the SEAM season.

This study reveals that the length, onset and demise dates of the SEAM season are important climatic features of the region. In conclusion, this study suggests that careful monitoring of the onset, the SEAM season could provide important information on the evolution of an ongoing SEAM. In fact, we even suggest from the analysis presented in this study that monitoring the low level winds over the northern equatorial Indian Ocean, Bay of Bengal, Gulfs of Martaban and Thailand and South China Sea could be very useful in understanding the seasonal variability of the SEAM. By the same token, monitoring the rain rate during the SEAM season will provide useful information on the potential demise of the wet season. Finally, monitoring of the demise would be equally helpful in characterizing the variation of the concluded SEAM as the length of the wet season seems to be a very robust climate feature of the region.

Acknowledgements

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