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The onset and advance of the Asian summer monsoon

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Abstract Based on the daily outgoing longwave radiation (OLR) data from National Oceanic and Atmospheric Administration (NOAA) satellites, the Climate Prediction Center's merged analysis of precipitation (CMAP) data and the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis dataset, the mean intraseasonal variability of the Asian summer monsoon (ASM) is investigated by using power spectrum analysis, band-pass filter, and diagnostic analyses. The processes of the onset and advance of monsoon over the southern part of Indochina Peninsula, the east coast of Bay of Bengal, the South China Sea and the Indian subcontinent are explored. It is found that there is an abrupt change in OLR, precipitation and zonal wind during the onset and advance of the ASM. It is also indicated that the southern part of Indochina Peninsula and the adjacent Andaman Sea is the region where the earliest onset of the ASM occurs in the 2nd pentad of May.

Keywords: Asian summer monsoon, intraseasonal variability, onset, advance.

The transition from the winter monsoon to summer monsoon is characterized by the abrupt change of the atmospheric circulation. Although many studies on the intraseasonal variation of the Asian summer monsoon (ASM) have been made, there are controversial views on the onset and advance of the ASM. Tao and Chen[1] pointed out that the SCS summer monsoon onset is the earliest onset of the ASM. The South China Sea summer monsoon(SCSSM) starts in middle May. Following this onset stage, the ASM gradually advances northward and northwestward in a stepwise fashion. With the increase of observational data, new notions about the intraseasonal evolution of the ASM are proposed. He *et al*.[2] found that during May there is a low value center of T_{BB} in Sumatra migrating northwestward and arriving the Indochina Peninsula, which indicates the establishment of summer monsoon convection over the Bay of Bengal and the Indochina Peninsula. Some studies have documented that the summer monsoon starts earliest over the eastern coast of the Bay of Bengal and then migrates to the SCS causing the onset of SCS summer monsoon in early May[3−6]. Furthermore, it has been noted in recent years that the earliest onset of the summer monsoon generally occurs over the southern part of western Indochina Peninsula in early May[7−10]. Ding *et al*.[11] summarized the results of the different studies and pointed out that the earliest onset of the ASM possibly occurs over a broad area near the Indochina Peninsula. However, the region of the earliest onset of the ASM is still not confirmed.

As for the onset process of SCS summer monsoon, there are also different points of views. Chang[12] proposed that the onset of the SCS summer monsoon is characterized by the intrusion of strong cold fronts into the SCS, the eastward retreat of the western Pacific subtropical high and the appearance of the southwest flow over the SCS in early-to-middle May. Yan[13] pointed out that the summer monsoon firstly appears over the northern part of the SCS, and subsequently the westerly prevails over the middle and southern parts of the SCS. Li and Qu[14] suggested that the onset of the SCS summer monsoon occurs over the northern and southern parts of the SCS simultaneously. Since the observations over the SCS region were scant in the past, these results should be reexamined by more observation data. South China Sea Monsoon Experiment (SCSMEX) in 1998 provided a large amount of observation data for further studies on the onset processes of SCS summer monsoon. Based on the SCSMEX observation data, it was found that the convective condensation heating associated with the development of the monsoon cyclone over the Bay of Bengal and the strong convection over the Indochina Peninsula broke down the subtropical high over the Bay of Bengal and brought about the final withdrawal of subtropical anticyclone from the SCS[15,16,6]. According to the results of the SCSMEX summarized by Ding *et al*.[11], the onset process of the SCS summer monsoon is depicted as follows: Tropical southwestly monsoon flow extends eastward from tropical eastern Indian Ocean. The rainy season over the Bay of Bengal and the Indochina Peninsula begins accompanying the influences of midlatitude systems. The southwestly monsoon flow extends eastward further to the SCS region. The ridge of the western Pacific subtropical high markedly weakens and retreats eastward. Finally there is an abrupt development of convective cloud, precipitation, low level southwestlies and high level northeastlies over the SCS region.

In the process of determination of the earliest onset dates of the ASM, it was found that the rainy season over the northern part of the SCS and the central Indochina Peninsula begins in late April to early May, regarded as the signal of the ASM onset. However Matsumoto[17] regarded this kind of rainfall as the pre-monsoon rain. It has been shown that the earlier appearance of the heavy rainfall over South China should not be recognized as the SCS summer monsoon rainfall in some recent literatures. Jin and Tao[18] pointed out that the southwestlies and the convective precipitation usually occur over the northern part of the SCS in late April to early May. This sort of precipitation is attributed to frontal rainfall which is caused by southward intrusion of cold air or by the variability of the western Pacific subtropical high and should not be regarded as the onset of the SCS summer monsoon. Li and Qu[14] also proposed that the frontal rainfall over South China in late April and May should not be simply regarded as the SCS summer monsoon rainfall. Although the southwestly flow and precipitation are the important signals of summer monsoon, they must be linked with cross-equatorial flow. The southwestly flow has prevailed over the coast of South China before the onset of the SCS summer monsoon. This southwestly flow comes from strong northwest flow of Indian subcontinent and Pakistan which turns to the southwestly flow over the Bay of Bengal. After the onset of the SCS summer monsoon, the southwestly flow over the northern part of the SCS and South China comes from the cross-equatorial flow from the Southern Hemisphere.

The ASM system consists of several subsystems. Wang[9] and Tanaka *et al*.[19] suggested that there are obvious differences in the intraseasonal variability associated with South Asian summer monsoon, East Asian summer monsoon and Western North Pacific summer monsoon (signified as WNPM). Many studies in the past have focused on the intraseasonal variability of the summer monsoon for sub-monsoon systems. The objective of the present study is to explore climatological mean intraseasonal variation for different subsystems of the ASM based on new observations and to focus on the abrupt changes of OLR, precipitation and zonal wind during the onset and advance of the ASM.

1 Data

Datasets used in the present research include: (1) OLR derived from NOAA satellite observations, (2) the Climate Prediction Center's merged analysis of precipitation (CMAP) data[20] derived by merging rain gauge observations, microwave and infrared satellite images, and numerical model outputs, and (3) the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis dataset[21]. The spatial resolution for all of these data is 2.5°×2.5° latitude-longitude grids. The pentad mean NCEP/NCAR reanalysis and precipitation cover the period 1979 to 1999. The climatological mean of NCEP/NCAR reanalysis and precipitation in 73 pentads is obtained by averaging the data from 1979 to 1999. Daily OLR is climatological mean averaged over the period from 1979 to 1995. The pentad mean OLR is computed from daily OLR data.

2 The intraseasonal stepwise variability of the ASM

In order to define the onset date of the ASM, a great variety of variables, such as precipitation, OLR, T_{BB} (equivalent Black Body Temperature of the cloud tops), temperature, vorticity, divergence and wind are usually employed as indices. Since the ASM rainfall is mainly convective precipitation, the OLR can represent not only the convective activity in low latitude but also the intensity of monsoon rainfall. In this paper the OLR is used to represent the variability of the monsoon intensity.

The intraseasonal variability of the ASM consists of MJO (Madden Julian Oscillation)[22] and other low-frequency oscillation in atmosphere. Lin and Wang[23] separated the intraseasonal variation of the ASM into fast annual cycle ranging from 7.5 to 60 days and slow annual cycle greater than 60 days. The fast annual cycle shows the key stages of intrseasonal variability associated with the ASM. In fact, the fast annual cycle defined by Lin and Wang is similar to the low-frequency oscillation of the ASM. However, in the fast annual cycle the periods great than 60 days are filtered out which contains partial information on intraseasonal time scale.

It is difficult to decide the key stages of intraseasonal variability of the ASM using the climatological pentad mean OLR directly since the ASM consists of circulations on different time scales. Therefore the OLR data are band-pass filtered to filter out the periods beyond the intraseasonal variability and stand out the characteristics of intraseasonal monsoon variability. In this paper, the dispersible power spectrum analysis[24] and band-pass filter[25] are employed to define the key stages of intraseasonal monsoon variability.

In order to ascertain the range of band-pass filter objectively, the dispersible power spectrum analysis is firstly performed on climatological mean daily OLR on every grid in Asian monsoon region (10°S—50°N, 60—180°E) before the climatological mean daily OLR is band-pass filtered. It is found that the most significant period falls in 365 days. This is a period associated with the annual cycle. During this period, confidence level for the dispersible power spectrum of OLR in the whole Asian monsoon region exceeds 0.05. It is apparent that this is a bogus period since the number of samples equals 365 days. When the periods equal 182, 122, 91, and 73 days, the dispersible power spectrum of OLR reaches confidence level in most Asian monsoon region, including South Asia, the SCS, subtropical East Asia, and the tropical Western North Pacific region. The geographical distribution of the dispersible power spectrum is quite similar in other periods (figure not shown). A significant test is performed on the mean of the dispersible power spectrum averaged on all of the grids in Asian monsoon region. The results show that just waves 1 to 4 (365 to 91 days) reach 0.05 confidence level (Fig. 1). The waves 2 to 12 (30 to 182 days) are selected as the primary variability periods of OLR according to the criteria that the F value of the dispersible power spectrum is greater than 1. That is to say, the primary variability periods of OLR in Asian monsoon region are from 30 to 182 days.

According to the results of power spectrum analysis, the OLR data are band-pass filtered. Because the 182-day period corresponds to the half-year period of climate variation, this period is removed also. Then the wave band of band-pass filter is fixed between 30 days and 122 days. The span is far greater than the recognized 30-60 days periods of low-frequency oscillation, but it still belongs to the time scales on intraseasonal variability. The 30-122-days band-pass filter is applied to climatological daily OLR on every grid in Asian monsoon region. The filtered daily OLR is averaged over 5 days to get the filtered pentad mean OLR.

Fig. 2 shows the variation of the pentad mean OLR during the summer monsoon period from the 5th pentad

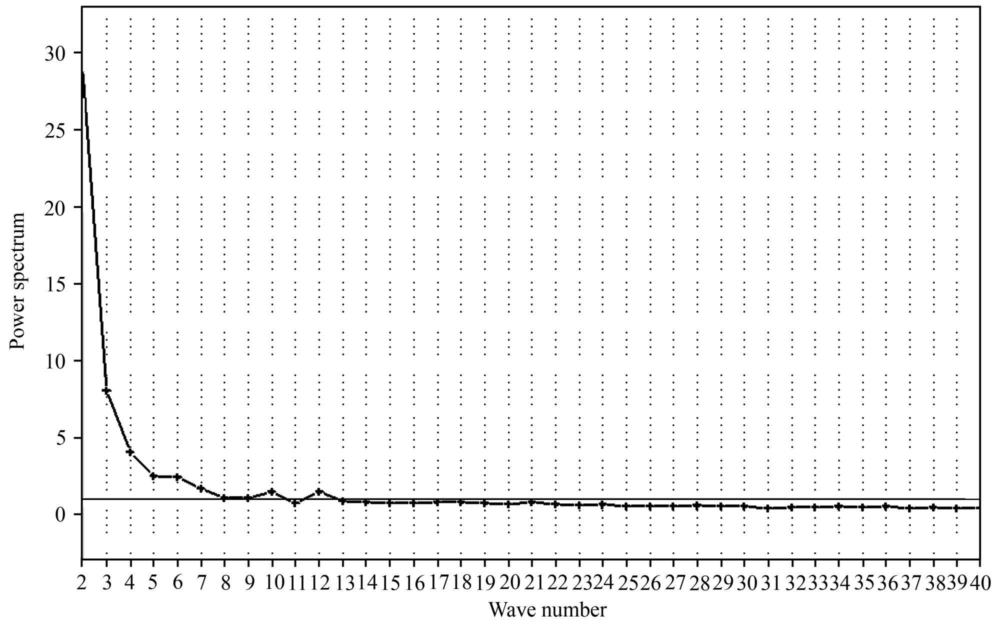

Fig. 1. The significant test associated with the mean of the dispersible power spectrum of climatological OLR averaged over Asian monsoon region (10°S—40°N, 40°—150°E). Abscissa indicates wave numbers (waves 2 to 40). Vertical coordinate denotes F value of the dispersible power spectrum. Horizontal solid line represents F=1.0.

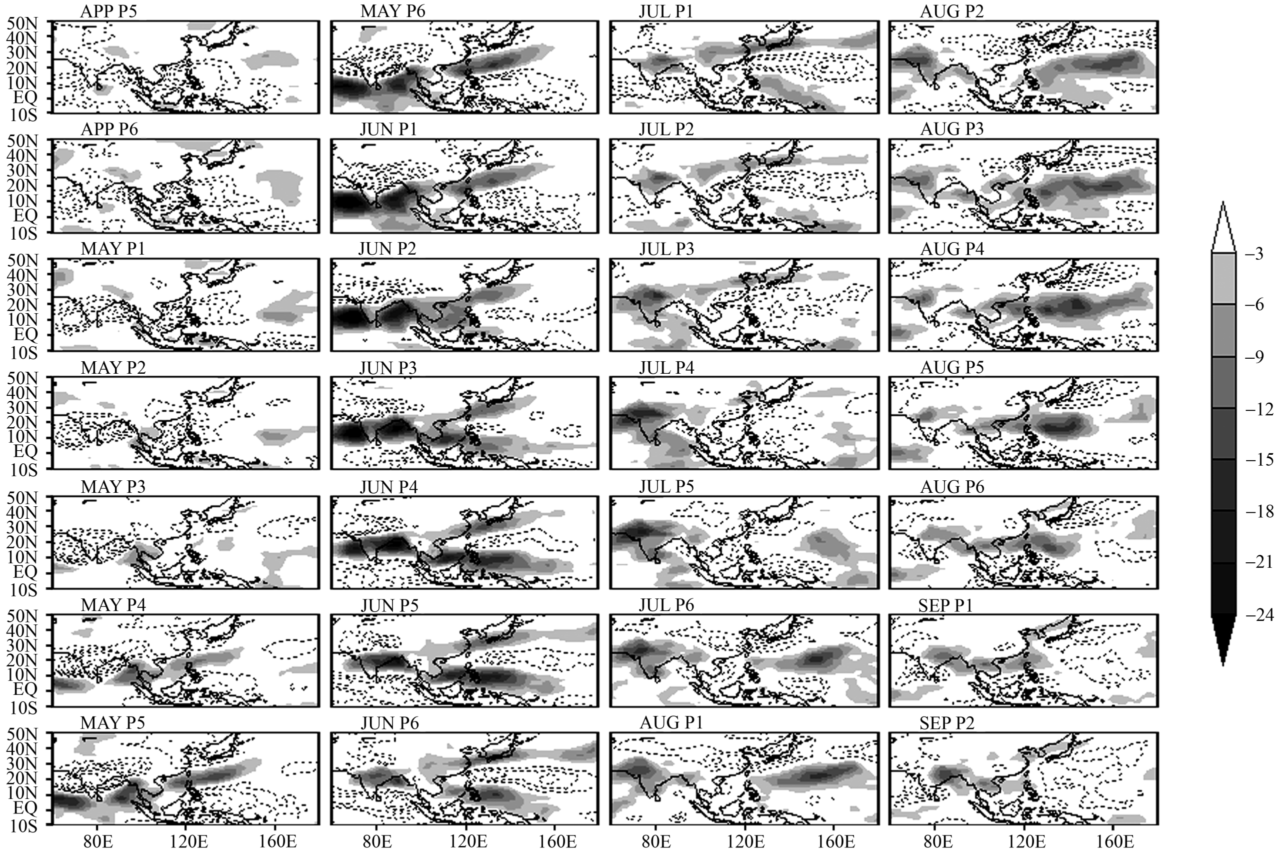

Fig. 2. The pentad variation of OLR in the ASM region from the 5th pentad of April to the 2nd pentad of September. Pentad data are 30—122-days band-pass filtered. The shaded area indicates that the value of OLR is less than $-3\mathrm{W \cdot m^{-2}}$, whose convection is strong. The dash line denotes the value of OLR is greater than $3\mathrm{W \cdot m^{-2}}$, whose convection is weak. Contour intervals are $3\mathrm{W \cdot m^{-2}}$.

of April to the 2nd pentad of September. Pentad data are 30-122-days band-pass filtered. In the 5th and 6th pentad of April, there is not any sign of the onset of summer monsoon over Asian monsoon region. By the 1st pentad of May, a little piece of active convection area appears in the northern part of Sumatra. Subsequently, the active convection intensifies and extends northwestward. The strong convective area reaches the southern part of Indochina Peninsula, Malaysia and the adjacent Andaman Sea in the 2nd pentad of May (Fig. 2, May P2). This is consistent with the results proposed by He *et al.*[2]. They found that the establishment of summer monsoon convection over the Indochina Peninsula in May was through the northwestward migration of the low value center of T_{BB} in Sumatra. There are 6 meteorological stations built by the Indian Meteorological Department in Andaman Islands[26]. According to observation data, it is found that the summer monsoon over the southern part of Andaman Islands (to the south of 10°N) starts on 5th May. The occurrence of summer monsoon over the northern part of Andaman Islands (12°—14°N) begins on 8th May. At that time, the convection over the Bay of Bengal to the north of Andaman Sea is inactive. At the present time, there are controversial views on the place where the onset of the ASM is earliest. Based on the results in Fig. 2 (May P2), it is revealed that the earliest onset of the ASM is located at the southern part of Indochina Peninsula and the adjacent Andaman Sea. The earliest onset date occurs at the 2nd pentad of May. We will discuss the onset of the ASM further in section 4.

The temporal variation of pentad mean OLR in Fig. 2 shows that the onset of the SCS summer monsoon occurs in mid-May. At that time, there is an active convection belt extending eastward from Indian Ocean to the south of Arabian Sea, through Andaman Sea, and SCS to the western Pacific. The centers of the deep convection belt are located in western Indian Ocean, Andaman Sea and the northern part of Philippine, respectively. This deep convection belt continues to move northward, and the intensity of the convection belt increases. At that time the Pre-Meiyu rainstorm period in

South China and Taiwan starts. By the 1st pentad of June, the deep convection belt intrudes into Arabian Sea, the Bay of Bengal, and the southern part of Indian Peninsula. Meanwhile, the Indian summer monsoon starts. The deep convection belt reaches the Indian subcontinent north of 20°N, Yangtze River Valley of China and the Pacific Ocean located to the south of Japan in the 3rd pentad of June. Almost simultaneously the monsoon trough over the Indian subcontinent and Intertropical Convergence Zone (ITCZ) in the tropical western Pacific become active; and the Meiyu (plum rain) period of the Yangtze River Valley occurs. Ye and Tao[27] proposed that atmospheric circulation undergoes an abrupt change in June. This is the time during which the abrupt change happens. Lin and Wang[23] called this period Grand Onset of the ASM. This is also the time when the tropical WNPM begins to become active. After the 3rd pentad of June the area of inactive convection belt (shown by dash line in Fig. 2) extends, suggesting that the western Pacific subtropical high develops and the ridge extends westward. From the 2nd pentad to the 3rd pentad of July the ridge of the western Pacific subtropical high extends to the middle reaches of the Yangtze River. The deep convection belt arrives at the Huanghe River Valley. The Meiyu period of the Yangtze River Valley ends, while the periods of Changma in Korea and the Baiu in Japan still prevail. After late July the western Pacific subtropical high (it is called Bonin high by Japanese meteorologists) reaches Japan. At that time the Baiu in Japan ends and the severe hot season in Japan starts. Simultaneously the ITCZ in the western Pacific suddenly moves northward up to 20°N over the tropical WNPM domain (130°—150°E, 10°—20°N)[28]. The area of active convection in tropical western North Pacific also migrates northward correspondingly. The activities of typhoon in western North Pacific enter the most high-frequency period. Ueda and Yasunari[29] found that the zone of the large-scale strong convective activity over western Pacific abruptly moves northward to near 20°N, 150°E in late July. Moreover, a strong monsoon trough occurs in this domain. The tropical WNPM enters the most active period in the 3rd and 4th pentads of August. The summer monsoon begins to retreat from North China in the 5th and 6th pentads of August. However, the convective activity in Indian monsoon and tropical Western North Pacific monsoon regions still remains active. The Indian summer monsoon starts to retreat in late August and early September, while the tropical WNPM does not retreat until early October.

In a word, the main characteristics of intraseasonal variability of the ASM are represented by 8 key stages: (1) in the 1st pentad of May, there is a precursory sign for the onset of the ASM; (2) the summer monsoon over the southern Indochina Peninsula and the adjacent Andaman Sea starts in the 2nd pentad of May; (3) the SCS summer monsoon outbreaks in the 4th pentad of May; (4) the Indian summer monsoon outbreaks in the 1s^{t} pentad of June; (5) the Meiyu period of the Yangtze River Valley occurs in the 3rd pentad of June; (6) the Meiyu period of the Jiang-Huai Valley ends in the 3rd pentad of July; (7) the Baiu in Japan ends in the 6th pentad of July, and the rainy season of North China starts; (8) the tropical western Pacific monsoon trough (ITCZ) deepens and migrates northward to the north of 20°N in the 4th pentad of August.

It can be found that the temporal-spatial variation of strong convection represented by shaded areas in Fig. 2 is a good indication for the intraseasonal variations of the ASM, and the southern Indochina Peninsula and the adjacent seas may be the earliest onset situation of the ASM. Following this initial outbreak, the Bay of Bengal summer monsoon, the SCS summer monsoon and Indian summer monsoon break out subsequently.

3 The onset and advance of the Asian summer monsoon

Heretofore there exist different points of view on the earliest onset place of the ASM. One way of thinking is that the earliest onset of the ASM occurs over the SCS in middle May[1,12]. Another point of view is that the earliest onset of summer monsoon occurs on the east coast of the Bay of Bengal in early May and then the SCS summer monsoon outbreaks[3−6]. In recent years some authors suggest that the earliest onset of summer monsoon usually starts over the southern part of western Indochina Peninsula in early May[7−10]. In section 3 of this paper we point out that the ASM firstly outbreaks over the southern part of Indochina Peninsula and the adjacent Andaman Sea in the 2nd pentad of May, which is consistent with the conclusions of the summer monsoon onset documented in some recent literatures[7−10]. Ding and Li *et al.*[11] summarized the results of different authors and proposed that the earliest onset of the ASM possibly occurs over the broad area near the Indochina Peninsula. However, there is not work to explore this issue further.

In this section, the onset and advance of the ASM are

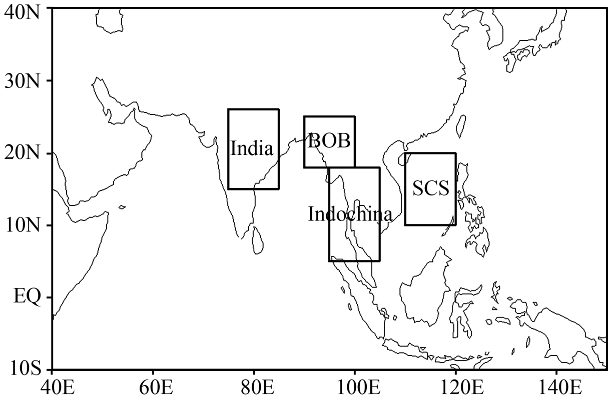

Fig. 3. The key regions of the ASM onset. India indicates the Indian subcontinent. BOB indicates the eastern Bay of Bengal. Indochina represents the southern part of Indochina Peninsula and the adjacent Andaman Sea. SCS represents the South China Sea.

reexamined using OLR, precipitation and zonal wind at 850 hPa. Fig. 3 shows several key regions of the ASM onset, including the SCS, the eastern Bay of Bengal (BOB), the southern Indochina Peninsula, and the Indian subcontinent.

The climatological pentad mean OLR is averaged over 4 key areas shown in Fig. 3, respectively, and the time series of area-averaged OLR are obtained (Fig. 4). The temporal variation of OLR may represent the onset and advance of summer monsoon in each region. In Fig. 4 abscissa indicates time (unit: pentad). Vertical coordinate denotes the value of area-averaged OLR (unit: W m^{-2}). The four curves in Fig. 4 show similar shapes of a filler with higher value of OLR on two sides and lower value of OLR in the middle. The value of OLR is higher from winter to spring, whereafter it decreases gradually with the seasonal transition and reaches the

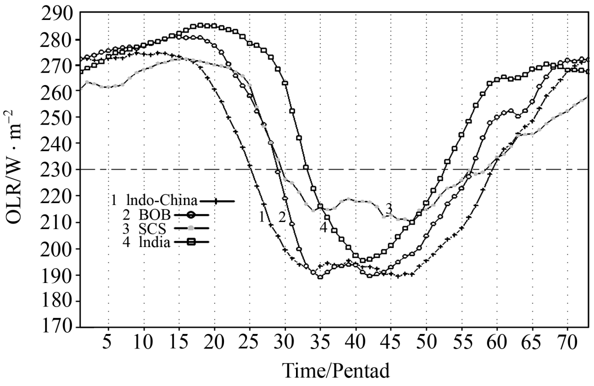

Fig. 4. The time series of area-averaged OLR associated with the key regions of the ASM. Abscissa indicates pentads. The horizontal dash line represents the value of OLR equal to 230W·m^{-2}. 1, southern Indochina Peninsula; 2, the eastern Bay of Bengal (BOB); 3, the SCS; 4, indicates the Indian subcontinent.

minimum value as the summer monsoon outbreaks. From late June to early August the minimum value of OLR persists and suggests that the convection over 4key areas is strong during summer monsoon period. After the summer monsoon season the value of OLR increases gradually. The convective activity over 4 key areas weakens correspondingly.

The threshold of summer monsoon onset is defined as the value of OLR is less than 230W m^{-2} (represented by the horizontal dash line in Fig. 4). It can be found that the intersections of the OLR values with the horizontal dash line are markedly different. This means that the monsoon onset for each area occurs in turn. As indicated in Fig. 4, the earliest onset of the ASM occurs in the southern part of Indochina Peninsula in the 2nd pentad of May. The summer monsoon over the Bay of Bengal starts in the 5th pentad of May. The SCS summer monsoon outbreaks in the 6th pentad of May. The Indian summer monsoon starts in the 3rd pentad of June. In addition, it is found that the summer monsoon in each area retreats in reverse order comparing with the onset. That is to say, the Indian summer monsoon retreats firstly, then the SCS summer monsoon and the summer monsoon over the Bay of Bengal retreat one after the other. The retreat of the summer monsoon over the southern Indochina Peninsula is the latest. It suggests that the monsoon which starts earliest retreats latest and vice versa. This is associated with the fact that the summer monsoon generally advances from south to north but retreats from north to south.

To prove the above-mentioned results derived from OLR, further study is made by analyzing of the precipitation and zonal wind at 850 hPa, because these two parameters can represent the characteristics of the monsoon onset and advance. The climatological pentad mean precipitation and zonal wind at 850hPa are averaged along the longitudes of the key regions associated with the ASM onset. The time-latitude sections of precipitation and zonal wind at 850 hPa over key regions of the ASM onset are shown in Fig. 5. Fig. 5(a)—(d) denote the Indochina Peninsula, the Bay of Bengal, the SCS, and the Indian subcontinent, respectively. Shaded area indicates the rainfall exceeding 6 mm·d^{-1}. The contours refer to zonal wind at 850 hPa. The thick solid line denotes the zero wind speed.

The easterly wind at 850 hPa prevails over the southern Indochina Peninsula and the adjacent seas from winter to spring (Fig. 5(a)). In the 1st pentad of May, the zero wind speed line suddenly turns to be vertical,

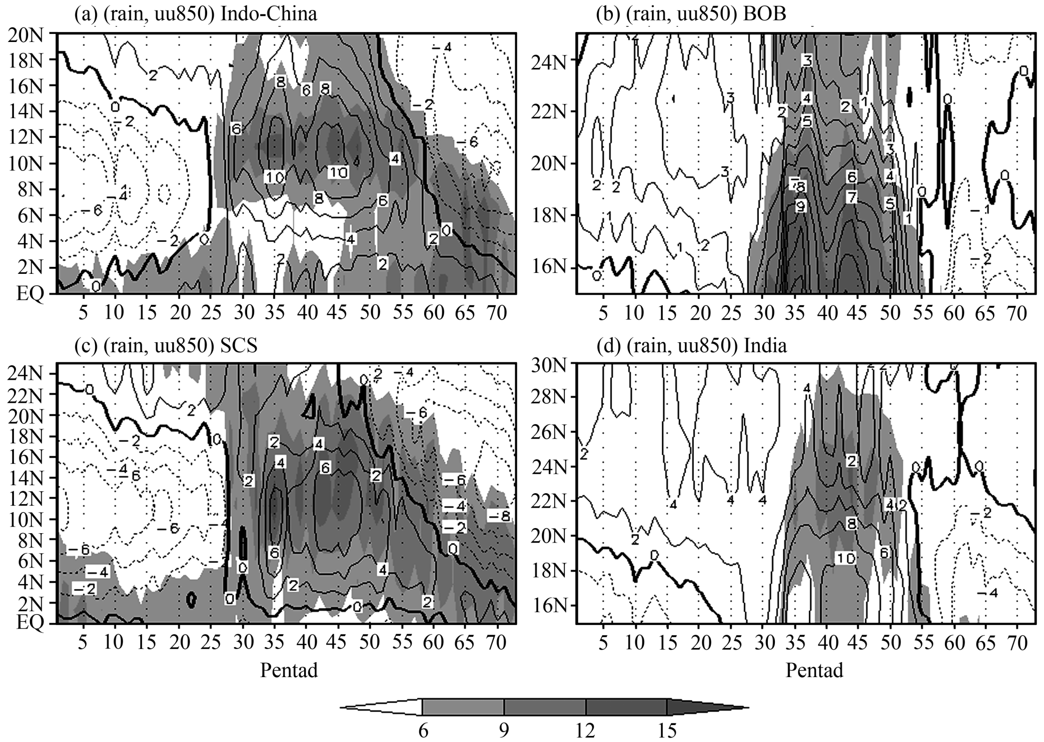

Fig. 5. The time-latitude sections of precipitation and zonal wind at 850hPa over key regions of the ASM, including (a) the Indochina Peninsula, (b) the Bay of Bengal, (c) the SCS, and (d) the Indian subcontinent. Shaded area indicates rainfall exceeding 6mm·d^{-1}. The contours refer to zonal wind at 850 hPa (unit: m·s^{-1}). The thick solid line denotes the zero wind speed.

and the zonal wind at 850 hPa suddenly changes into the westerly flow over the southern Indochina Peninsula and the adjacent seas. Meanwhile, the heavy precipitation suddenly appears in the whole area. The abrupt intraseasonal change of precipitation well coincides with that of wind, indicating the onset of the ASM. The heavy precipitation and westerly flow over the latitudinal bands between 7° and 16°N persist till October. After October the westerly flow gradually changes into easterly from north to south, indicating the withdrawal of the summer monsoon.

The westerly flow prevails over the Bay of Bengal from January to early October (Fig. 5(b)). There exists weak easterly over the Bay of Bengal in December then it turns into the westerly flow again in January. The reason for this is that there is low pressure trough (called the India-Burma trough) existing over the Bay of Bengal in winter and spring. Thus the westerly flow prevails over the Bay of Bengal at all times before the onset of summer monsoon. The westerly flow intensifies apparently after the onset of summer monsoon. At that time the westerly flow comes from the cross-equatorial flow from the Southern Hemisphere. The heavy precipitation suddenly occurs in the area in the 3rd pentad of May, indicating the onset of summer monsoon over the Bay of Bengal. The heave precipitation disappears in late September and early October. Meanwhile, the summer monsoon over the Bay of Bengal retreats.

The sudden occurrence of the westerly flow and heavy precipitation in the SCS (Fig. 5(c)) is more obvious than that in the southern Indochina Peninsula. An abrupt change in the wind from an easterly to a westerly regime occurs in the 4th pentad of May. Simultaneously the heavy precipitation occurs in the SCS. This suggests the climatological onset of the SCS summer monsoon starts over the southern and northern parts of the SCS simultaneously. Li and Qu[14] proposed that the onset of the SCS summer monsoon occurs over the northern and southern parts of the SCS simultaneously. After late September the summer monsoon retreats gradually. The easterly flow prevails over the SCS. The heavy precipitation exists between the equator and 4°N before the onset of the SCS summer monsoon. It is associated with the activity of ITCZ in this region. In addition, there exists intermissive strong precipitation over South China and the north part of the SCS from late April to early May. It suggests that the pre-flood-period rainfall over South China starts earlier. But various previous studies[14,17,18] have documented that the pre-flood-period rainfall over South China should not be attributed to the SCS summer monsoon rainfall. At present it is generally recognized that the mean onset date of the SCS summer monsoon is around middle May. This is consistent with the results obtained in this paper.

On the Indian subcontinent (Fig. 5(d)), the westerly flow prevails over the area south of 20°N in summer, while the easterly flow prevails in other seasons. The area north of 20°N experiences westerly flow in four seasons. It is also associated with the activities of the India-Burma trough in winter and spring. The heavy precipitation occurs over the Indian subcontinent in the 2nd pentad of June, indicating the onset of Indian summer monsoon. The active and break of Indian summer monsoon can be identified according to the appearance and disappearance of heavy precipitation over the area south of 20°N. The Indian summer monsoon weakens and retreats in late September.

According to the intraseasonal variability of precipitation and zonal wind at 850 hPa, it is seen that the sequence of the ASM onset agrees with the results derived from OLR data. Mann-Kendall test is performed in 4 time series in Fig. 4, respectively (figure not shown). The result shows that the sequence of beginning of abrupt changes in 4 key regions is consistent with the sequence of the ASM onset. Summarizing all of these results, it can be concluded that the earliest onset of the AMS occurs over the southern part of Indochina Peninsula and the adjacent Andaman Sea in the 2nd pentad of May.

4 Conclusions and discussion

In this paper, the climatological mean intraseasonal evolution of the ASM is investigated based on new observations and the results from the previous studies. There is not any sign for the summer monsoon onset in Asian monsoon region in late April. A small scale area of active convection appears over the north part of Sumatra in the 1st pentad of May. When the active convection area extends northward, a strong convection area appears over southern Indochina Peninsula and the adjacent Andaman Sea in the 2nd pentad of May, indicating the onset of Asian summer monsoon. The SCS summer monsoon outbreaks in the 4th pentad of May. At the same time, a deep convection belt extends eastward from Indian Ocean to the south of Arabian Sea, through Andaman Sea, to the SCS and West Pacific. Then the onset and advance of the ASM are represented by a series of events along with the deep convection belt extending northward, eastward and westward. The Indian summer monsoon starts in the 1st pentad of June. The Meiyu period of the Yangtze River Valley begins in the 3rd pentad of June. The Meiyu over the Huaihe River Valley ends in the 3rd pentad of July. The Baiu in Japan ends in the 6th pentad of July, meanwhile the rainy season of North China starts. The tropical western Pacific monsoon trough (ITCZ) deepens and moves northward up to the north of 20°N in the 4th pentad of August.

The characteristics of the onset and advance of the ASM over several regions, such as the southern Indochina Peninsula, the east coast of the Bay of Bengal, the SCS and the Indian subcontinent, are examined. The scenario associated with the abrupt changes of OLR, precipitation and zonal wind at 850 hPa in the process of the onset and advance of the ASM over different areas is proposed. Based upon the comparison of onset dates and advance of summer monsoon in each area, it is proposed that the earliest onset of the ASM occurs over southern Indochina Peninsula and the adjacent Andaman Sea in the 2nd pentad of May, then the onset of the monsoon over the Bay of Bengal, the onset of the SCS summer monsoon and the onset of Indian summer monsoon outbreak in order.

Based on the research results of SCSMEX in 1998, it is found that the outbreak of the SCS summer monsoon derives from tropical eastern Indian Ocean and Indochina Peninsula. The results in this paper show (Fig. 2) that the earliest onset of the ASM occurs over southern Indochina Peninsula in the 2nd pentad of May. By the 3rd pentad of May, there is not deep convection belt over the SCS, while the strong convection has appeared over the area located to the east of Philippine. The SCS summer monsoon outbreaks in the 4th pentad of May. At the same time, a deep convection belt appears over the area from the SCS to western Pacific, with a center of deep convection belt located to the north of Philippine. The strong convective centers around Indochina Peninsula and around Philippine are separated. Thus it is difficult to conclude whether the onset of the SCS is derived from Indochina Peninsula or from the western Pacific located to the east of Philippine. In this regard, further study is needed to investigate the origin of the onset of the SCS summer monsoon. In addition, whether or not the SCS summer monsoon starts in the northern and southern parts of the SCS simultaneously deserves a further study.

Since the results obtained in this study are derived from the climatological mean data, there are year-to-year variations in the onset dates and advance of the ASM. The present study provides only a climatology mean onset and advance of the ASM. As for the inter-annual variations of the onset and advance of the ASM, it will be discussed in another paper.

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