ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 23, NO. 6, 2006, 940–950

The Summer Monsoon Onset over the Tropical Eastern Indian Ocean: The Earliest Onset Process of the Asian Summer Monsoon

DING Yihui[1] (丁一汇) and HE Chun*[2] (何 春)

[1]*National Climate Center, Beijing* 100081

[2] *Nanjing Institute of Meteorology, Nanjing University of Information Science and Technology, Nanjing* 210044

(Received 19 April 2006; revised 20 Spetember 2006)

ABSTRACT

The onset process of the tropical eastern Indian Ocean (TEIO) summer monsoon (TEIOSM) and its relationship with the cross-equatorial flows are investigated via climatological analysis. Climatologically, results indicate that the earliest onset process of the Asian summer monsoon occurs over the TEIO at pentad 22 (April 15–20). Unlike the abrupt onset of the South China Sea (SCS) summer monsoon, the TEIOSM onset process displays a stepwise advance. Moreover, a close relationship between the TEIOSM development and the northward push of the cross-equatorial flows over 80°–90°E is revealed. A difference vorticity center, together with the counterpart over the southern Indian Ocean, constitutes a pair of difference cyclonic vortices, which strengthens the southwesterly wind over the TEIO and the northerly wind to the west of the Indian Peninsula from the end of March to late May. Therefore, the occurrence of the southwesterly wind over the TEIO is earlier than its counterpart over the tropical western Indian Ocean, and the cross-equatorial flows emerge firstly over the TEIO rather than over the Somali area. The former increases in intensity during its northward propagation, which provides a precondition for the TEIOSM onset and its northward advance.

Key words: Indian Ocean, summer monsoon, onset

doi: 10.1007/s00376-006-0940-2

1. Introduction

Based on many studies on the Asian summer monsoon (ASM), Tao and Chen (1987) suggested that the huge ASM system consists of two subsystems, the Indian and the East Asian monsoon systems, which are independent of and interact with each other, and the East Asian summer monsoon onset firstly takes place over the northern South China Sea (SCS) in early May, then proceeds northwards and westwards stepwisely, while the Indian summer monsoon bursts out in early June and then advances northwestwards. Thus, the seasonal transition in East Asia takes place the earliest over the SCS, with a mean date at penta 28, i.e., the fourth pentad in May (Murakami et al., 1996; Yan, 1997; Xie et al., 1997; He et al., 2000; Qian et al., 2000; Feng et al., 2001; Jin and Tao, 2002; Qiao et al., 2002; Liang and Wu, 2002;). However, as the satellite data are used widely in research, investigators found that the ASM onset may not occur firstly over the SCS, and then much effort has been devoted to the studies of the characteristics of the summer monsoon activities over the Indochina Peninsula and its impacts on the ASM (Matsumoto, 1987; Lau and Yang, 1987; Wu and Zhang, 1998; Zhang and Wu, 1998; Zhang et al., 2004; Qian et al., 2004). After summarizing numerous studies, Ding (2004) has indicated that in most cases the ASM onset firstly occurs in the central and southern part of the Indochina Peninsula, foreshadowed by the circulation changes and development of convective activities over the tropical eastern Indian Ocean (TEIO) and the Bay of Bengal (BOB), and summer monsoons over the TEIO, the Indochina Peninsula and the SCS are components of Southeast and East Asian monsoon system. In fact, the SCS summer monsoon onset is thought to be the result of the development and eastward extension of the TEIO summer monsoon (TEIOSM). In this process, the development of a vortex pair over the BOB and the southern Indian Ocean plays an important role. For

---

*E-mail: eBird219@cma.gov.cn

instance, Zhang et al. (2004) showed that one center with positive vorticity and another center with negative counterpart are observed to develop, respectively, over the 5°–20°N area of the BOB and the southern Indian Ocean during the process of the summer monsoon onset over the Indochina Peninsula and the SCS. Over the near-equatorial region between the two centers, the southwesterly wind speeds up and propagates eastwards, and together with the easterlies from the Western Pacific, favors the onset of the summer monsoon to occur firstly in the Indochina Peninsula. So the summer monsoon activities over the TEIO are closely related to the onset and advance of the ASM, and the southwesterly wind over the TEIO may directly affect the summer monsoon onset process over the downstream regions. Therefore, it is very necessary to reveal the summer monsoon onset process over the TEIO to further understand the onset feature of the ASM.

Ding (2004) compared various results on the onset dates obtained by many investigators, and Li and Qu (2000) also presented their results. In these results the summer monsoon onset over the Indian Ocean is also involved. However, following discrepancies need be clarified: (1) different definitions of onset dates, (2) the onset date of summer monsoon over the TEIO shows great discrepancy with a large range from April 11–15 (the earliest) to May 20 (the latest). In this paper, a synthetic way including the 850 hPa circulation, the 850 hPa pseudo-equivalent potential temperature (PPET, $\theta_{\rm se}$) and OLR data is utilized to study the TEIOSM onset.

2. Data and methods

2.1 *Data*

Datasets utilized in the present research include: (1) 850 hPa wind and surface sensible/latent heat flux taken from European Center for Medium Range Weather Forecasts (ECMWF) Reanalysis for a 45 years period of 1 September 1957–31 August 2002 (ERA 40). In ERA40, data-assimilation schedule and model are improved, as well as more observational and satellite data are utilized, and both results in its good quality (Uppla, 2001). (2) The Outgoing Longwave Radiation (OLR) data taken from the product of Climate Diagnostics Center (CDC), National Oceanic and Atmospheric Administration (NOAA). It covers a time range from 1 June 1974 to 2 February 2004. Due to data unavailability during 17 March–31 December 1978, only the datasets from 1979 onwards are used in the present research. The spatial resolution for both datasets is 2.5° × 2.5°.

Datasets averaged for 73 pentads a year are derived from data sources (1) and (2). Then the 1979–2001 pentad-by-pentad mean data are produced, which are our analysis base in this paper.

2.2 *Method to define the summer monsoon onset*

Many monsoon indices have been proposed to describe the South Asian summer monsoon, summarized by Wang and Fan (1999), such as the all India rainfall index (AIRI) (Mooley and Shukla, 1987), Webster-Yang index (WYI) (Webster and Yang, 1992), and monsoon Hadley index (MHI) (Goswami et al., 1999), and also many Chinese researchers have proposed various SCS summer monsoon indices. In general, of these indices exist more or less shortcomings in contrast to the simple but efficient South Oscillation Index (He et al., 2001).

Therefore, it is necessary to explore the primary features of the tropical summer monsoon over Asia and the adjacent regions to find out an efficient method to define the summer monsoon onset. Over these regions, the activity of summer monsoon is primarily characterized by the westerlies prevailing at low levels and easterlies at upper levels with intense convection and rainfall, according to which many indices are defined. Recently, researchers incline to define onset dates with circulation and convection/rainfall features. Considering the circulation aspect, some investigators examine the wind shear between the upper and the low level, but some researchers suggest that the changes of the upper and the low level circulation are not simultaneous in the ASM onset process. For example, in the SCS summer monsoon onset process, Gao et al. (2001) indicated that changes in the upper-level wind is one pentad earlier than that in the low-level wind. Yan (1997) also found that the low-level southwesterly wind and the upper-level northeasterly wind cannot be established at the same time, while over the southern part the 200-hPa northeasterly wind appears earlier than the 850-hPa southwesterly wind and the date when the low-level southwesterly wind is set up is thought to be that of summer monsoon onset. But over the northern part the 200 hPa northeasterly wind emerges somewhat later compared with the low level southwesterly wind, thus the method to consider both the upper and the low level circulation simultaneously is not likely to be very effective. In fact, the prevailing low level westerly wind with abundant rainfall is most prominent during the summer monsoon onset phase. Therefore, the prevailing 850 hPa westerlies should be selected as one variable to define the summer monsoon onset. Because of the lack of conventional observations over oceans, and the OLR data measured directly from

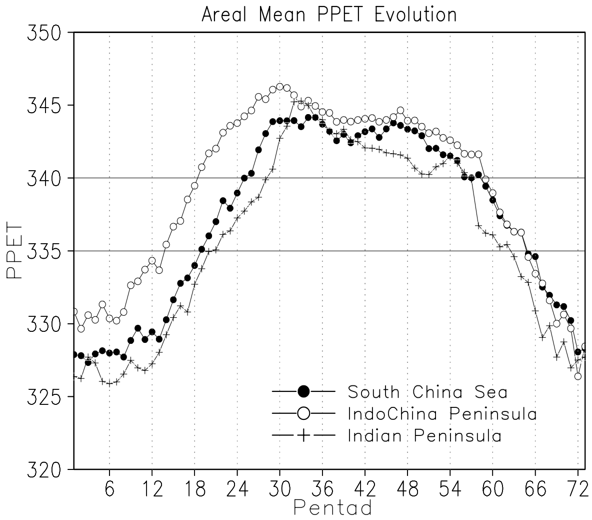

Fig. 1. Pentad-by-pentad evolution of areal mean 850 hPa θ_{se} (K) over the South China Sea (10°–20°N, 110°–120°E), the Indochina Peninsula (10°–20°N, 100°–107.5°E) and the Indian Peninsula (10°–20°N, 75°–80°E) region.

satellites with higher reliability to represent convections over tropics, OLR is also adopted to investigate the convection characteristics in present study.

In addition, some investigators insist that the thermodynamic variables, for example, the 850 hPa θ_{se}=340 K or θ_{se}=335 K isolines may be regarded as the leading zone of the Asian summer monsoon, or θ_{se}=335 K isoline as a criterion to define the onset date of the SCS summer monsoon. However, according to the mean conditions of 1979–2001 calculated in this study, the 850 hPa θ_{se} is already higher than the threshold of 335 K or 340 K prior to the summer monsoon onset (Fig. 1). So the increase of the 850 hPa θ_{se} to a certain value is just a necessary condition for the summer monsoon onset, but it is not sufficient when applied directly to define the onset.

According to the above discussion, the following requirements are given to define the summer monsoon onset:

(1) 850 hPa westerlies prevail,

(2) OLR$\leqslant$240 W m^{-2}, and

(3) 850 hPa $\theta_{\mathrm{se}} \geqslant 340$ K.

3. Climatological study on the summer monsoon onset over the TEIO

3.1 *Onset process features*

The TEIO is where strong convection (OLR$\leqslant$240 W m^{-2}) starts to advance northwards steadily the earliest at the same latitude from the Western Pacific Ocean to the western Indian Ocean. From the longitude-time cross section of OLR (Fig. 2), it is seen that:

(1) For the western Pacific Ocean (142.5°–145°E) region (Fig. 2a), the OLR=240 W m^{-2} isoline (hereafter referred as OLR240), has a slow northward advance until May, which is then accelerated from early June.

(2) For the SCS (112.5°–115°E) region (Fig. 2b), OLR240 advances northwards in middle May abruptly so remarkably as to arrive beyond 17.5°N, denoting an obvious bursting out of the SCS summer monsoon.

(3) For the Indochina Peninsula (97.5°–107.5°E) region (Fig. 2c), OLR240 emerges from pentad 21, but at this time the middle-latitude westerly wind prevails. OLR240 and the tropical westerlies then advance northwards. Over the whole Indochina Peninsula, active convection appears at pentad 23 and 850 hPa westerlies at pentad 27.

(4) For the eastern part of the TEIO (92.5°–95°E) region (Fig. 2d), OLR240 starts to advance northwards at pentad 19 and crosses 7.5°N at pentad 22, which is nearly simultaneous with the appearance of the westerlies. Then OLR240 extends northwards rapidly in May.

(5) For the western part of the TEIO (82.5°–85°E) region (Fig. 2e), OLR240 proceeds northwards to 7.5°N at pentad 22, and crosses 10°N in middle May.

(6) For the middle part of the tropical western Indian Ocean (67.5°–70°E) region (Fig. 2f), OLR240 jumps northwards to 5°N and 10°N in early and middle May, respectively, and at the end of May it arrives to the region north of 17.5°N rapidly.

(7) For the western part of the tropical western Indian Ocean (52.5°–55°E) region (Fig. 2g), OLR240 exists until the end of May, with a limited latitudinal range and very short lifetime.

The onset of the deep convection over the TEIO differs significantly from that over the SCS: the latter exhibits an obvious abrupt jump with the OLR240 proceeding from 7.5°N to the region to the north of 17.5°N in just one pentad, while the former is characterized by a stepwise process with a stationary phase between every two northward advance jumps. Each jump spans about less than five latitudes.

The above analysis indicates that over the TEIO active convection extends northwards distinctly earlier than over the western Pacific Ocean, the SCS, the Indochina Peninsula, and the tropical western Indian Ocean. Therefore, over the Asian summer monsoon region, cumulus convection, a dominant characteristic denoting the summer monsoon establishment, takes place the earliest over the TEIO.

The latitude-time cross section of the 850 hPa θ_{se} and wind field, as well as the difference between θ_{se} averaged over 1000–700 hPa and that averaged over 600–300 hPa, i.e.,

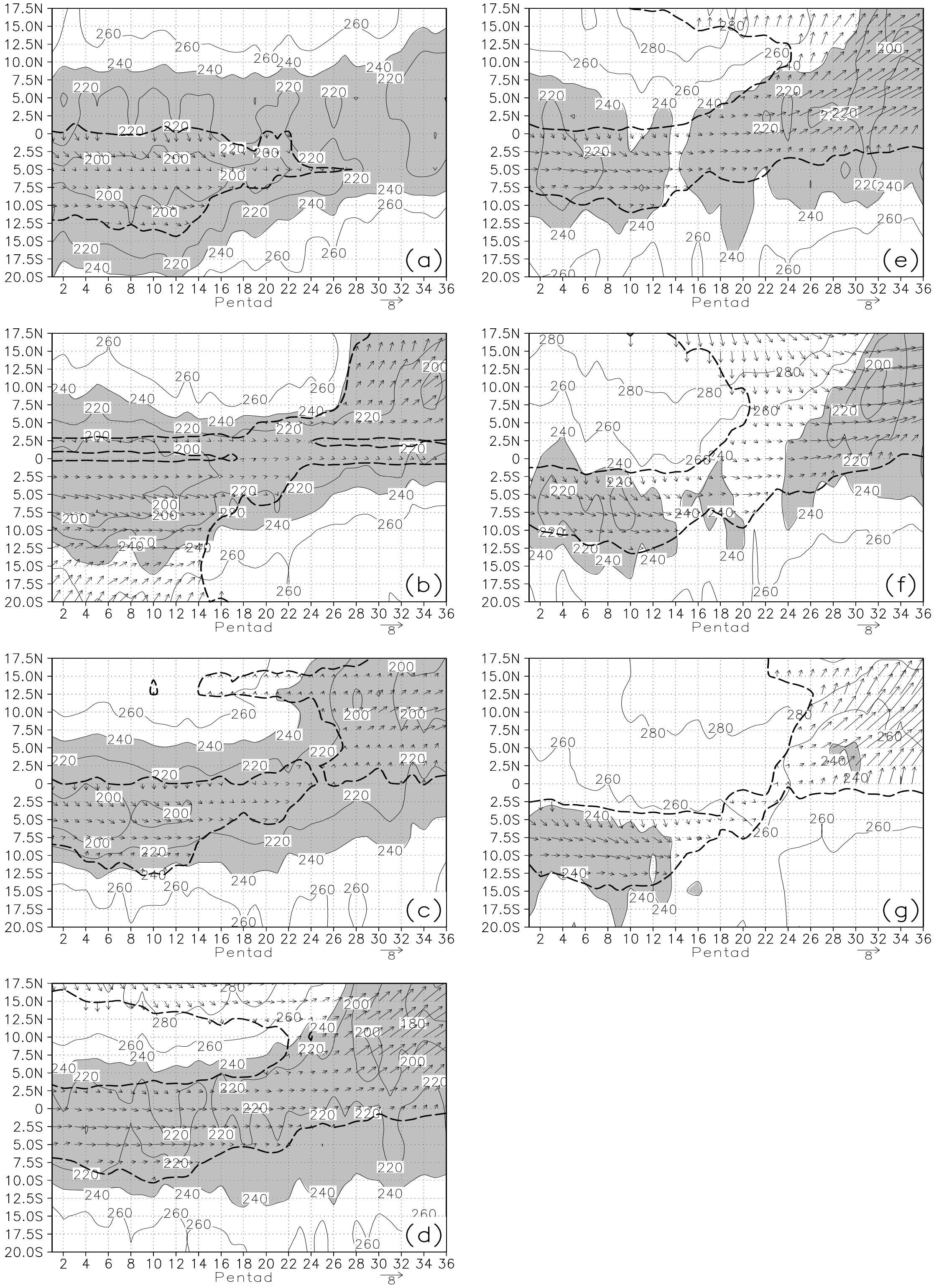

Fig. 2. Latitude-time (pentad) cross section of OLR (W m^{-2}) over (a) the western Pacific (142.5°–145°E), (b) the South China Sea (112.5°–115°E), (c) the Indochina Peninsula (97.5°–107.5°E), (d) the eastern part of the TEIO (92.5°–95°E), (e) the western part of the TEIO (82.5°–85°E), (f) the middle part of the western Indian Ocean (67.5°–70°E) and (g) the western part of the western Indian Ocean (52.5°–55°E). Westerly wind is shown and shades indicate OLR<240. The bold dashed lines denote $U = 0$.

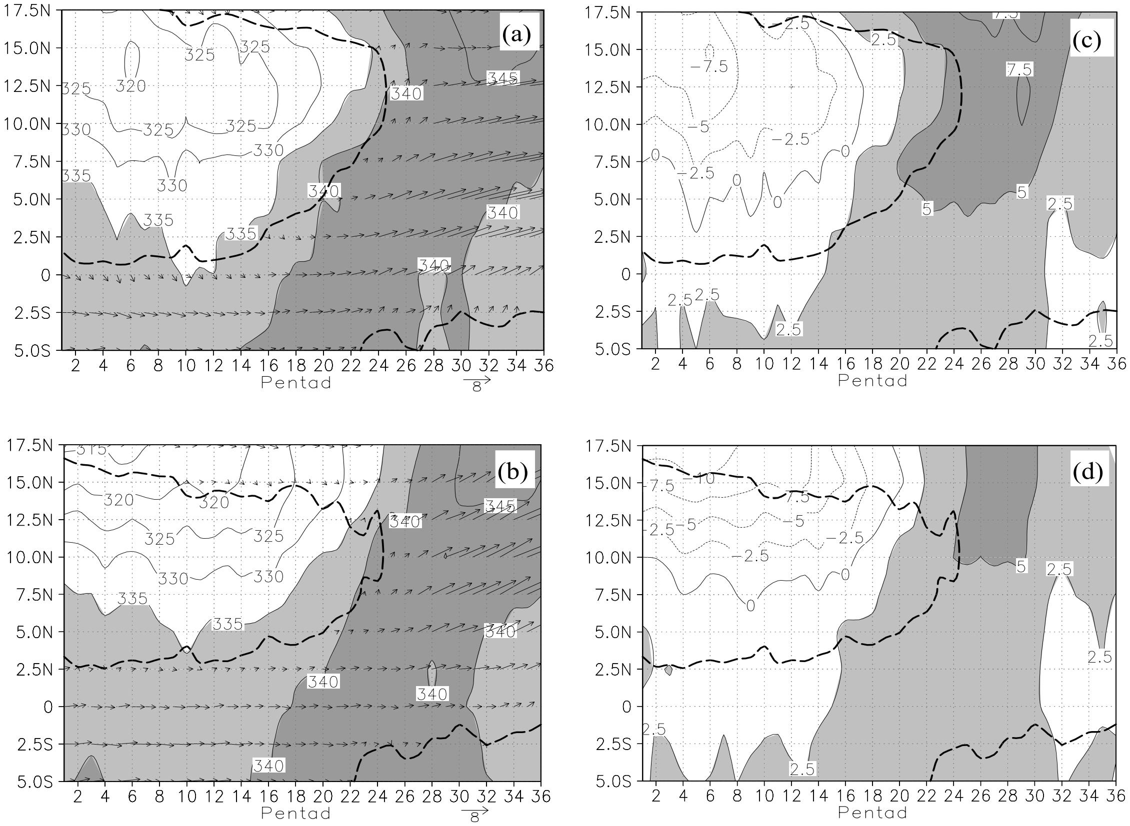

Fig. 3. Latitude-time (pentad) cross section of 850 hPa $\theta_{\rm se}$(K) with westerly wind (m $\rm s^{-1}$) (left column) and $\Delta\theta_{\rm se}$ (K) (right column) over the western part of the eastern the (82.5°–85°E) (the upper row) and the eastern part of the eastern Indian Ocean (92.5°–95°E) (the lower row). Light and dark shadings indicate $\theta_{\rm se} > 335$ K, 340 K and $\Delta\theta_{\rm se} > 2.5$ K, 5 K, respectively. The bold dashed lines denote $U = 0$.

$$\Delta\theta_{\rm se} = \theta_{\rm se}(1000 - 700\ {\rm hPa}) - \theta_{\rm se}(600 - 300\ {\rm hPa})$$

is also analyzed in this paper (Fig. 3). Over the TEIO, when the deep convection extends northwards to the north of the equator, $\Delta\theta_{\rm se}$ varies in advance of the wind changing from easterly to westerly flow, suggesting that the atmosphere is already convectively unstable before the arrival of westerly wind. Favorable for the development of convection, the development of $\Delta\theta_{\rm se} > 2.5$ K, which indicates the very unstable condition of the atmosphere, occurs before $\theta_{\rm se} = 340$ K.

Compared with Fig. 2, during the phase when the deep convection extends northward to as far as 10°N, the convection changes ahead of the westerly wind over the eastern part of the TEIO. In contrast, they change synchronously over the western part of the TEIO, indicating that the deep convection there is probably triggered by the westerly wind. The averaged wind fields at pentad 15–18 (Fig. 4a) and at pentad 21–23 (Fig. 4b), as well as their difference (Fig. 4c) reveal that at pentad 15–18, when the deep convection over the TEIO does not extend northwards yet, a cyclonic circulation already appears over the ocean close to the northern part of Sumatra south of the BOB, which favors the generation of deep convection. Thus OLR over the eastern part of the TEIO north of the equator becomes lower than 240 W $\rm m^{-2}$ before April. From pentad 15–18 to pentad 21–23, as the southwesterly wind increases continuously, the western part of the TEIO north of equator is gradually dominated by southwesterly wind, and the deep convection spread northwards because of the unstable condition.

According to the above analysis, over the eastern part of the TEIO to the north of the equator, before the westerly wind arrives, OLR is already lower than 240 W $\rm m^{-2}$. But over the western part, OLR lowers down as a result of the deep convection, which is triggered by the westerly wind. It may be concluded that the date when the westerly wind arrives denotes the onset of the summer monsoon over the TEIO.

3.2 *Climatological onset date*

Figure 5 presents the evolution of the northernmost

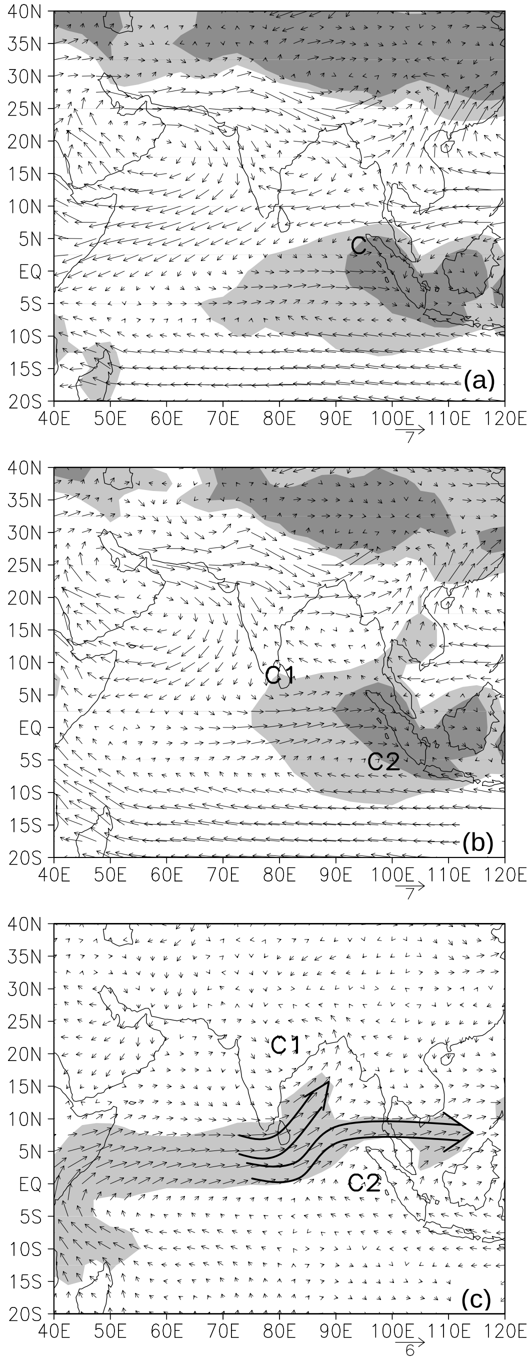

Fig. 4. 850 hPa Wind fields and OLR distributions ($\mathrm{W\,m^{-1}}$) of (a) pentad 16–18 and of (b) pentad 21–23 and also (c) their difference wind fields ($\mathrm{m\,s^{-1}}$). Light and dark shadings in (a) and (b) denotes OLR<240 and 220 W $\mathrm{m^{-1}}$ respectively while that in (c) indicates wind velocity $\geqslant$2.1 $\mathrm{m\,s^{-1}}$. C, C1 and C2 are cyclonic vortex centers.

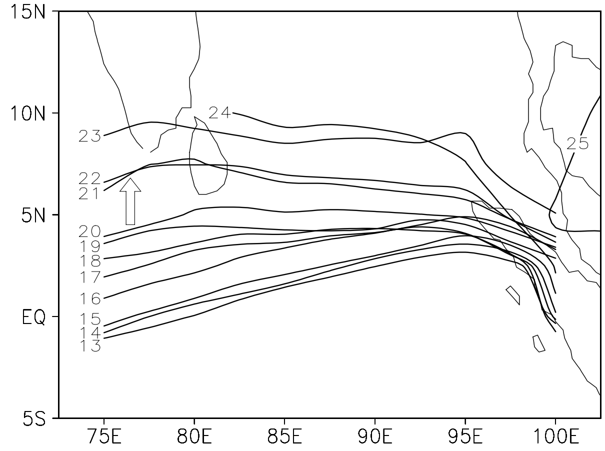

Fig. 5. Pentad-by-pentad positions of 850 hPa $U = 0$ $\mathrm{m\,s^{-1}}$ isotachs from pentad 13 to pentad 25 over the eastern equatorial Indian Ocean to the north of the equator.

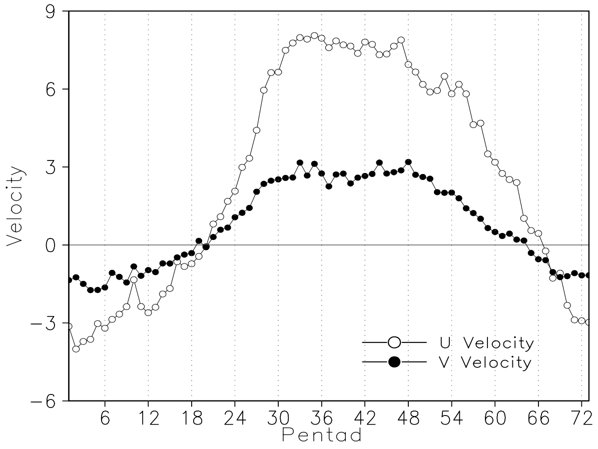

Fig. 6. Pentad-by-pentad evolution of 850 hPa zonal wind velocity and meridional wind velocity over the eastern equatorial Indian Ocean (0°–10°N, 75°–100°E) to the north of equator. Units: $\mathrm{m\,s^{-1}}$.

boundary of 850 hPa westerlies (i.e., $U = 0\ \mathrm{m\,s^{-1}}$ isolines, hereafter referred as $U0$) over the eastern Indian Ocean to the north of the equator at pentad 13 to 25. It is shown that the westerlies move northwards from early March to the end of April. Over this region, $U0$ crosses the equator entirely at pentad 16, then it advances northwards slowly with less than 3 latitudes covered in the following 4 pentads. Abruptly, at pentad 21, $U0$ jumps to the southern end of the BOB, covering even more latitudes than that in the past 4 pentads. And it almost keeps stationary at pentad 22. At the same time, the velocity of the mean 850 hPa zonal and meridional wind over the TEIO to the north of the equator both increases significantly and the zonal wind changes into westerly wind (Fig. 6). Furthermore, the 850 hPa θ_{se} to the south of the BOB Has not reached 340 K yet until pentad 22 (Fig. 3a and b). Because OLR240 has arrived prior to the westerly

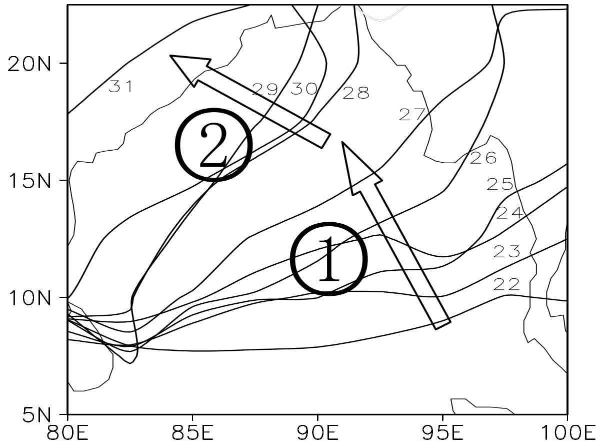

Fig. 7. Pentad-by-pentad positions of OLR=240 W m^{-1} isolines during summer monsoon onset process from pentad 13 to pentad 25 over the northern part of the eastern equatorial Indian Ocean and the BOB. The two arrows and related circled numbers denote the two jumps of the propagation of OLR=240 W m^{-1} isolines.

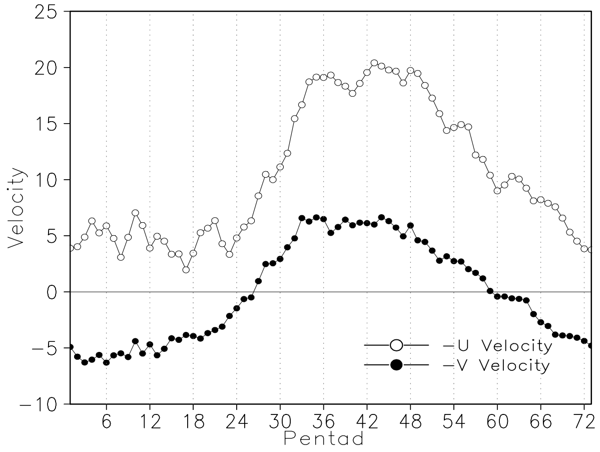

Fig. 8. Pentad-by-pentad evolution of 200 hPa (a) easterly wind velocity and (b) northerly wind velocity over the eastern equatorial Indian Ocean (0°–10°N, 75°–100°E) to the north of equator. Units: m s^{-1}.

wind, the TEIOSM onsets at pentad 22. $U0$ jumps to the northern part of Sri Lanka at pentad 23, thus the summer monsoon onset starts over the southern BOB.

After a relative stabilization at pentad 24, at pentad 25 the southwesterly wind extends to the BOB and the southwestern Indochina Peninsula, as these regions begin to be dominated by westerly wind. According to Fig. 7, from pentad 22 to pentad 27, OLR240 advances northwards at a roughly constant rate, followed by an evident westward jump at pentad 28. In the following two pentads, its position swings. At pentad 31, when OLR240 jumps westwards again, active convection affects the whole BOB. So the monsoon onset process over the BOB looks stepwise.

Summer monsoon bursts out over the Indochina Peninsula and the SCS at pentad 27 (Zhang et al., 2004) and 28, respectively (Figure not shown).

Only slight variations of the 200 hPa zonal and meridional winds (Fig. 8) are found in the process of the TEIOSM establishment, indicating that the upper level system varies slowly in comparison with the low level monsoonal flow. In correspondence with the summer monsoon onset over the Indochina Peninsula and the SCS, an evident increase in the 200 hPa easterly and northerly wind is found at pentad 27. The subsequent persisting increase in both the easterly and northerly wind velocity until middle June is closely associated with the onset of Indian summer monsoon, and the high wind velocity does not decrease in August. Therefore, during the TEIOSM onset process, the remarkable circulation change takes place at low levels, which differs significantly from those of the Indochina Peninsula, the SCS and the Indian summer monsoon onset process.

4. Relationship between TEIOSM and the cross-equatorial flow

The variations of meridional wind over the equatorial Indian Ocean suggest that there exist two cross-equatorial airflows (Fig. 9a). The one located over ∼80°–90°E begins to appear at pentad 18, while the other, lying to the west of 70°E, and with greater longitudinal range than the former, appears at pentad 22. The southerly wind of the latter is much stronger than that of the former. The cross-equatorial flows situated between 60° and 70°E emerge the latest at pentad 26.

The increase in southwesterly wind is remarkable in the TEIOSM onset process (Fig. 4), which is influenced by the cross-equatorial flows over ∼80°–90°E. The cross-equatorial flow emerges over 80°–85°E at as early as pentad 16 (Fig. 9a), and the western part of $U0$ crosses the equator at the same time (Fig. 5). In the TEIOSM onset process, the 85°–95°E mean 850 hPa meridional wind velocity displays a two-step acceleration (Fig. 9b). At pentad 19, when the 85°–95°E mean 850 hPa meridional velocity along the equator exceeds 0, the OLR over the western part of the TEIO (Fig. 2d) starts to advance northwards. At pentad 22, when the meridional velocity gets to the second increase (Fig. 9b), the OLR advances northwards again (Fig. 2d) and the TEIOSM onset.

These facts indicate that the evolution of the TEIOSM is closely related to the development of the cross-equatorial flows over the tropical eastern Indian Ocean.

In order to demonstrate why there exists a timing discrepancy in the emergence of the cross-equatorial

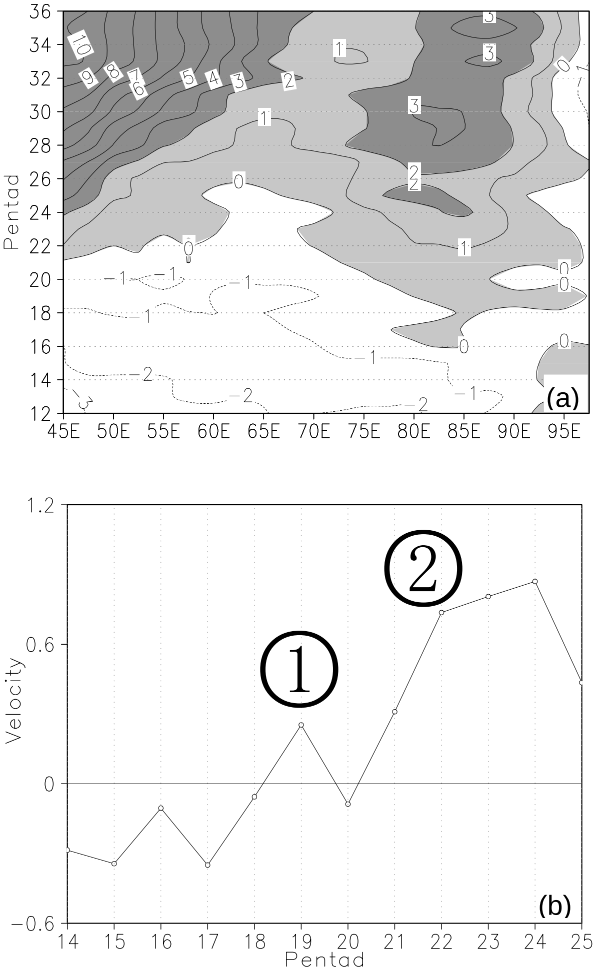

Fig. 9. (a) Time (pentad)-longitude cross section of 850 hPa meridional wind velocity (m s^{-1}) along the equator in the domain of the Indian Ocean, while light and dark shades denote westerly wind more than 1 and 2 m s^{-1}, respectively. (b) Mean 850 hPa meridional velocity (m s^{-1}) over 85°–95°E along the equator.

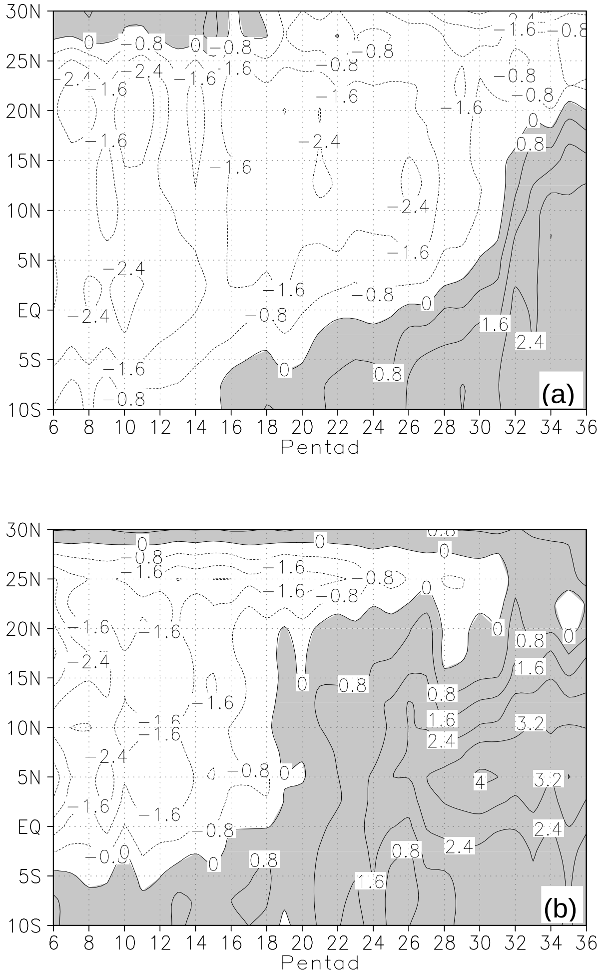

Fig. 10. Latitude-time (pentad) cross section of 850 hPa meridional wind velocity (m s^{-1}) over (a) the Indian Ocean (62.5°–67.5°E) and (b) the Indian Ocean (82.5°–87.5°E). Shades indicate meridional wind velocity >0 m s^{-1}.

flows over different regions of the Indian Ocean, the latitude-time cross section (Fig. 10) for the averaged meridional wind over 62.5°–67.5°E (Area A), where the cross-equatorial flows emerge the latest, and 82.5°–87.5°E (Area B), where the earliest, are investigated, respectively. The primary difference is that, from late March to the end of May, along with the northward advancement of the southerly wind over Area B, the northerly wind over Area A between 5° and 25°N strengthens and forms a northerly wind maximum which lasts until late May or early June, and then vanishes when the southerly wind expands northwards rapidly.

Figure 11a depicts the difference in wind and vorticity fields between pentad 16–18 and pentad 13–15, from which we can observe a pair of anomalous vorticity centers, with one over India, the BOB and the Indochina Peninsula, and the other over the southern hemisphere, and the region between these two centers is dominated by intense southwesterly anomalies. Anomalous westerly wind with greater southerly component is found over 80°E as well as to the east of it, while the anomalous northerly wind is located to the west of the anomalous vorticity center over India. Thus the conclusion is that the difference wind filed may be resulted from the meridional wind distribution associated with the anomalous vorticity pair, which is in favor of an earlier occurrence of the cross-equatorial flows over the eastern part of the TEIO.

Comparing Fig. 11b (showing the difference of wind field and vorticity between pentad 21–23 and pentad 16–18) with Fig. 11a, it is clear that the anomalous vorticity center over the Indian Peninsula enhances

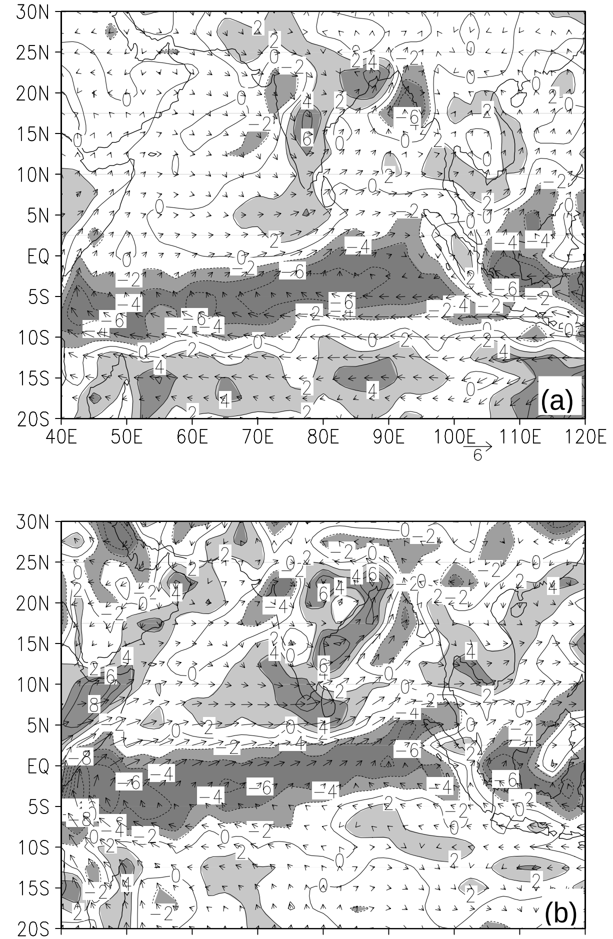

Fig. 11. 850 hPa difference wind ($\mathrm{m\,s^{-1}}$) field and vorticity ($\mathrm{s^{-1}}$) distribution (a) between pentad 16–18 and pentad 13–15 and (b) between pentad 21–23 and pentad 16–18.

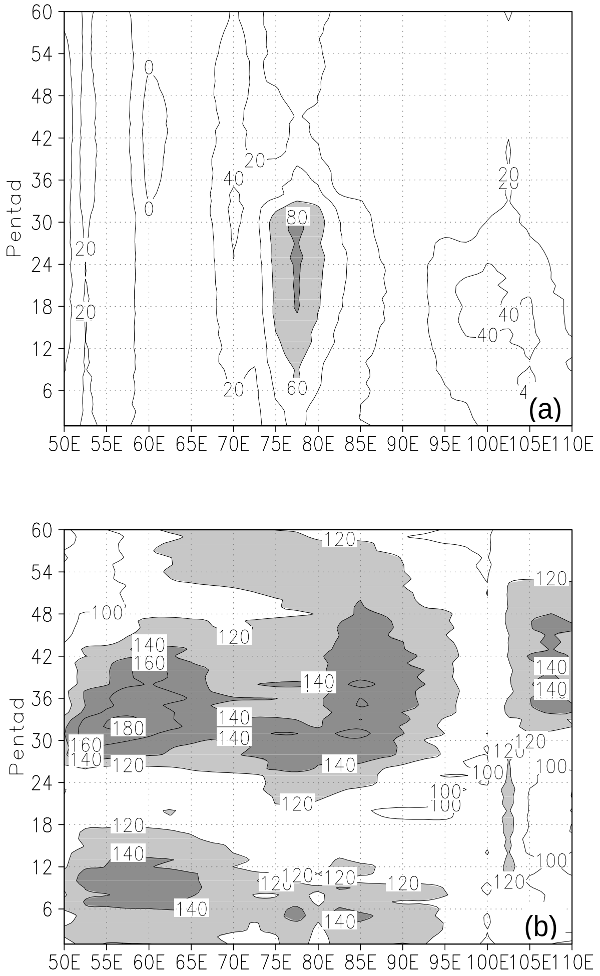

Fig. 12. Time (pentad)-longitude cross section of (a) (10°–25°N) mean surface sensible heat flux (W $\mathrm{m^{-2}}$) and (b) (0°–7.5°N) mean surface latent heat flux (W $\mathrm{m^{-2}}$). The light and dark shades in (a) denote value is greater than 60 and 80 W $\mathrm{m^{-2}}$, and in (b) 120 and 140 W $\mathrm{m^{-2}}$, respectively.

with time, so does the anomalous southwesterly wind over the TEIO, as is in agreement with the southwesterly wind augment and its northward advance.

The numerical simulation made by He et al. (2000) has indicated that the existence of the Indian Peninsula and the related land heating effect have great impacts on the intensification of Indochina–Burma trough from May to June, which is favorable for the onset of summer monsoon over the SCS, but hampers that over the Indian Peninsula. During the summer monsoon establishment process over the tropical Indian Ocean, the presence and intensification of the anomalous vorticity center over the Indian Peninsula is likely to be correlated to the great surface sensible heat flux (Fig. 12), where it is much stronger than other regions in spring to summer with a maximum occurring in April and May. Over the ocean to the south of India, there emerges the intense surface latent heat flux, which decreases in March to early April and strengthens after middle April. The low level atmosphere is heated by the intense surface heat flux, and consequently the atmosphere geopotential height decreases as to generate an anomalous cyclone over this region.

Therefore, as a result of the intense surface heat flux, an anomalous cyclone over India and the adjacent ocean to the south is observed, which favors the continuous intensifications of the southwesterly wind over the TEIO and the northerly wind to the west of India, so the cross-equatorial southwesterly airflow emerges the earliest over the TEIO. Tomas and Webster (1997) proposed that the development of the southerly wind over the tropical eastern Indian Ocean may be related to inertial instability caused by northward shift of zero-line of absolute vorticity. The southwesterly wind firstly has its onset over the TEIO, then it advances northwards successively, as to form the TEIOSM.

5. Conclusions

The onset process of the Asian summer monsoon over the tropical Indian Ocean is explored. It is clear that the initial stage of the summer monsoon onset over the tropical Indian Ocean is found over its eastern part, i.e. the tropical eastern Indian Ocean and is closely related to the occurrence of the cross-equatorial flow at 80°–90°E. Main conclusions are as follows.

(1) The Indian Ocean summer monsoon onset occurs the earliest over the tropical eastern Indian Ocean to the north of the equator at pentad 22. In this onset process，the active convection, in a stepwise way, and 850 hPa westerlies extend northwards. When the 850 hPa westerly wind jumps to Sri Lanka at pentad 21, and the 850 hPa $\theta_{\rm se}$ over this area also increases to 340 K at pentad 22, the tropical eastern Indian Ocean summer monsoon onset occurs. This result presents a clear difference in timing and regions with respect to the climatologic onset dates summarized by Ding (2004).

(2) Different from the remarkable explosive features of the South China Sea summer monsoon, the TEIOSM onset process is characterized by a stepwise advance, and is mainly marked by the arrival of the southwesterly wind.

(3) Each increase of active convection over the tropical eastern Indian Ocean is closely related to the intensification of the cross-equatorial flows at 80°–90°E, i.e., there exists a close relationship between the evolution of the tropical eastern Indian Ocean summer monsoon and the development of the cross-equatorial flows. The intense surface heat flux over India and the ocean to the south results in the formation of the difference vorticity center over this region, and combined with the other one over the southern Indian Ocean, a difference cyclone pair forms, which is in favor of the intensification of the southwesterly wind over the tropical eastern Indian Ocean and the northerly wind over western India from the end of March to late May. The cross-equatorial flow emerges the earliest over the tropical eastern Indian Ocean, which intensifies and advances northwards continuously, thus providing a precondition for the tropical eastern Indian Ocean summer monsoon onset and its northward advance.

Acknowledgments. This work is supported by the Ministry of Science and Technology of China (Grant No. 2001BA611B01).

REFERENCES

Ding, Y., 1994: Monsoons over China. Kluwer academic publishers, 420pp.

Ding, Y., 2004: Seasonal march of the East-Asia summer monsoon. *East Asian Monsoon*, C. P. Chang, Ed., World Scientific Publishing, 562pp.

Feng Ruiquan, Wang Anyu, Wu Chisheng, Lin Wenshi, Lin Jianheng, Gu Zhiming, and Tan Zhiwen, 2002: Climatological features of the establishment of the South China Sea summer monsoon I 40-year mean. *Journal of Tropical Meteorology*, **17**, 345–354. (in Chinese)

Gao Hui, He Jinhai, Tan Yanke, and Liu Junjie, 2001: the South China Sea monsoon onset dates in 1958–1997. *Definition of the South China Sea Summer Monsoon Onset and Monsoon Index*, He et al., Eds., China Meteorological Press, 42–48. (in Chinese)

Goswami, B. N., V. Krishnamurthy, and H. Annamalai, 1999: A broad scale circulation index for the interannual variability of the Indian summer monsoon. *Quart J. Roy. Meteor. Soc.*, **125**, 611–633.

He Jinhai, 2001: Introduction. *Definition of the South China Sea Summer Monsoon Onset and Monsoon Index*, He et al., Eds., China Meteorological Press, 1–3. (in Chinese)

He Jinhai, Xu Haiming, Zhou Bing, and Wang Lijuan, 2000: Discussions of the large scale characteristics of the South China Sea summer monsoon establishment and the formation mechanism. *Climatic and Environmental Research*, **5**, 333–344. (in Chinese)

Jin Zuhui, and Tao Shiyan, 2002: The Onset of the Summer Monsoon over the South China Sea and Its Active and Break Periods. *Climatic and Environmental Research*, **7**, 267–278. (in Chinese)

Lau, K. M., and S. Yang, 1987: Climatology and interannual variability of the Southeast Asian summer monsoon. *Adv. Atmos. Sci.*, **14**, 141–161.

Li Chongyin, and Qu xin, 2000: Large scale atmospheric circulation evolutions associated with summer monsoon onset in the South China Sea. *Scientia Atmospheric Sinica*, **24**, 1–14. (in Chinese)

Liang Jianyin, and Wu Shangseng, 2002: A study of southwest monsoon onset date over the South China Sea and its Impact Factors. *Chinese J. Atmos. Sci.*, **26**, 829–844. (in Chinese)

Matsumoto, J., 1987: Seasonal transition of summer rainy season over Indochina and adjacent monsoon region. *Adv. Atmos. Sci.*, **14**, 231–245.

Mooley, D. A., and J. Shukla. 1987: Variability and forecasting of the summer monsoon rainfall over India. *Monsoon Meteorology*, C.-P. Chang and T. N. Krishnamurti, Eds., Oxford University Press, 26–59.

Qiao Yunting, Jian Maoqiu, and Luo Huibang, 2002: Different characteristics of precipitation over foursubregions of South China Sea during summer monsoon and the abrupt change. *Journal of Tropical Meteorology*, **18**, 38–44. (in Chinese)

Qian, W., and D. Lee, 2000: Seasonal march of Asian summer monsoon. *International Journal of Climatology*, **20**, 1371–1386.

Qian Yongfu, Jiang Jing, Zhang Yan, Yao Yonghong, and Xu Zhongfeng, 2004: The earliest onset area of the tropical Asian summer monsoon and its mechanism. *Acta Meteorolica Sinica*, **42**, 129–139. (in Chinese)

Tao, S., and L. Chen, 1987: A review of recent research on the East Asian summer monsoon in China. *Monsoon Meteorology*, C-P Chang and T. N. Krishnamurti Eds., Oxford University Press, 60–92.

Tomas, R., and P. J. Webster, 1997: On the location of the intertropical convergence zone and near-equatorial convection: The role of inertial instability. *Quart. J. Roy. Meteor. Soc.*, **125**, 1445–1482.

Uppala, S., 2001: ECMWF Re-Analysis, 1957–2001, ERA40. Workshop on Reanalysis, ECMWF Reading, Uk, 10pp. [Available online from www.ecmwf.inf/publications/library/ecpublications/proceedings/ERA40-reanalysis-workshop/index.html]

Wang Anyu, Wu Chisheng, Lin Wenshi, Yang Yan, Feng Ruiquan, Gu Zhiming, and Liang Jiajing, 1999: The definition of the advance and retreat of the summer monsoon in China. *Plateau Meteorology*, **18**, 400–408. (in Chinese)

Wang, B., and Z. Fan, 1999: Choice of South Asian summer monsoon indices. *Bull. Amer. Meteor. Soc.*, **80**, 629–638.

Webster, P. J., and S. Yang, 1992: Monsoon and ENSO: Selectively interactive systems. *Quart. J. Roy. Meteor. Soc.*, **118**, 877–926.

Wu Guoxiong, and Zhang Yongsheng, 1998: Thermal and Mechanical Forcing of the Tibetan Plateau and the Asian Monsoon Onset. Part I: Situating of the Onset. *Scientia Atmospherica Sinica*, **22**, 825–838. (in Chinese)

Xie An, Liu Xia, and Ye Qian, 1997: Equatorial vortex and the onset of summer monsoon over south China Sea. *Acta Meteorolica Sinica*, **55**, 611–619. (in Chinese)

Yan Junyue, 1997: Climatological Characteristics on the onset of the South China Sea Southwest Monsoon. *Acta Meteorolica Sinica*, **55**, 174–186. (in Chinese)

Zhang, Y., T. Li, B. Wang, and G. Wu, 2002: Onset of the summer monsoon over the Indochina Peninsula: Climatology and interannual variations. *J. Climate*, **15**, 3206–3221.

Zhang Yongsheng, and Wu Guoxiong, 1998: Diagnostic investigation of mechanism of onset of Asian summer monsoon and abrupt seasonal transitions over northern hemisphere Part 1. *Acta Meteorolica Sinica*, **56**, 513–528. (in Chinese)

Zhang, Z. J., C. L. Chan, and Y. Ding, 2004: Characteristics, evolution and mechanisms of the Summer Monsoon onset over Southeast Asia. *International Journal of Climatology*, **24**, 1461–1482.