Clim Dyn (2016) 47:1961–1970
DOI 10.1007/s00382-015-2944-z

Effect of the early and late onset of summer monsoon over the Bay of Bengal on Asian precipitation in May

Nan Xing[1,2] · Jianping Li[1,2] · Lanning Wang[1,2]

Received: 2 May 2015 / Accepted: 7 December 2015 / Published online: 19 December 2015

Abstract The impact of early and late Bay of Bengal (BoB) summer monsoon (BoBSM) onset on Asian precipitation in May is investigated. When the BoBSM occurs earlier (later), May rainfall tends to be enhanced (suppressed) in the southern Indian peninsula (SIP), the Indochinese peninsula (ICP), southwest China (SWC) and the South China Sea (SCS), while south China (SC) rainfall tends to be suppressed (enhanced). When the BoBSM occurs earlier than the climatological mean (late April), strong convective activity emerges earlier over the BoB, which causes local strong convective heating earlier. Then, earlier spread of heating in the BoB towards both sides leads to earlier retreat of the subtropical highs in the western Pacific (WPSH) and Indian Ocean outwards the BoB. Thus, compared to the climatological mean, the two subtropical highs present larger retreat outwards the BoB and smaller meridional extent over the SCS and Arabian Sea in May, which contributes to positive heating anomalies over the SCS and Arabian Sea. Therefore, anomalous cyclonic circulations occur over the BoB, SCS and Arabian Sea in May. Anomalous cyclonic circulation is favorable for low-level convergence over the SIP, and thus resulting in local heavy rainfall. Associated with cyclonic circulation anomalies over the BoB and SCS, anomalous low-level convergent winds and ascending flows favor positive precipitation anomalies in the ICP, SWC, and SCS, while anomalous northeasterlies and descending flows affected by the southward retreat of the WPSH lessen SC rainfall. In late onset years the opposite occurs.

Keywords Summer monsoon onset · The Bay of Bengal · Asian precipitation

1 Introduction

Monsoon onset is the most important subseasonal variability in monsoon systems. It characterizes the beginning of the rainy season and large-scale convection, and an abrupt change of atmospheric circulation (e.g., Wang and Ding 1997; Hsu et al. 1999; Li and Qu 2000, Zhang and Li 2008, Pai and Nair, 2009; Saini et al. 2011). Therefore, early or late monsoon onset may have an appreciable influence on precipitation, leading to variation in the timing of agrarian ploughing and planting in monsoon-affected regions.

Many onset indices have been proposed based on abrupt changes in large-scale atmospheric structures, with horizontal wind (e.g., Webster and Yang 1992; Lu and Chan 1999; Li and Zeng 2002; Wang et al. 2004) and precipitation (e.g., Tao and Chen 1988; Webster et al. 1998; Zhang et al. 2002b) being the most common atmospheric variables used for defining onset indices. The onset dates of the Asian summer monsoon (ASM) have some extent difference owing to differences in indices or definitions of indices. Thus, many unified onset indices have been proposed with the deepening of research (e.g., Mao et al. 2002a, b; Wang and LinHo 2002; Li and Zhang 2009). The relevant studies based on these onset indices have indicated that, despite some discrepancies in onset indices and data, the onset of the ASM occurs firstly over the Bay of Bengal (BoB) in late April to early May (e.g., Wu and Zhang 1998; Mao et al. 2002a, b; Wang and LinHo 2002; Li and

✉ Jianping Li
ljp@bnu.edu.cn

1 College of Global Change and Earth System Science, Beijing Normal University, Beijing, China

2 Joint Center for Global Change Studies, Beijing, China

Zhang 2009). After the onset of the BoB summer monsoon (BoBSM), the rain belt moves northeastward and northwestward, accompanying the summer monsoon onset on either side of the BoB.

ASM onset has significant interannual variability, and the range between the earliest and latest onset dates of the ASM can exceed 1 month (e.g., Lau and Yang 1997; Krishnamurthy and Shukla 2000; Mao and Wu 2007; Pai and Nair 2009; Jiang 2011). Many authors have discussed the factors affecting the interannual variation of monsoon onset, such as the El Niño Southern Oscillation (ENSO) and snow accumulation over the Tibetan Plateau (e.g., Mao and Wu 2007), the timing of the establishment of the subtropical high in South Asia (e.g., Wang and Guo 2012), and the interannual variation of local sea surface temperature (SST) (e.g., Jiang and Li 2011; Yu et al. 2012). Equally, many studies have been devoted to understanding the impact of early and late monsoon onset in the BOB on the subsequent monsoon onset and climate over local and remote regions.

Results from Liu et al. (2002) indicate that latent heating associated with the BoBSM onset may result in vertical ascent over the northern South China Sea (SCS) as an asymmetric Rossby wave response, causing overturning of the meridional temperature gradient over the SCS, which leads to the SCS summer monsoon (SCSSM) onset. Tamura and Koike (2010) show that convective heating around the BoB induces an upper tropospheric warming southwest of the Tibetan Plateau, which is necessary for the Indian summer monsoon (ISM) onset. Besides the important climatic influence of early and late BoBSM onset on monsoon onset in other regions, the BoBSM onset date also has a wide spread influence on rainfall and water vapor transport in Yunnan, China (Yan et al. 2003; Chen et al. 2006). Furthermore, Huang et al. (2004) find that early and late SCSSM onset affects summer (June–August) rainfall in the Yangtze River basin in China through its influence on the meridional position of the subtropical high in the western Pacific (WPSH). Liu and Ding (2008) show that a teleconnection pattern develops over an area from the west of the Indian peninsula to the Yangtze River basin after the ISM onset. ASM circulation systems undergo a series of changes accompanying the development of the teleconnection pattern, triggering the onset of the Meiyu in the Yangtze River basin, China. Because the BoBSM occurs earlier in the season, an early or late BoBSM onset has a more important role in climate over local and remote regions.

May is the key month that the ASM and rainy season occur over wider regions in Asia (e.g., Wang and LinHo 2002; Li and Zhang 2009) and the transition month that weather and climate begin to adjust in the Northern Hemisphere (e.g., Lau and Yang 1997), so May climate, especially precipitation should be of concern for its great influence on agriculture and economy in Asia. The BoBSM usually occurs in late April, and previous studies (Yan et al. 2003; Chen et al. 2006) indicated the relationship between the BoBSM onset and on rainfall and water vapor transport in May in Yunnan, China, therefore, May precipitation in Asia is probably affected by the early and late BoBSM onset. However, there has been little focus on the impact of the early and late BoBSM onset on precipitation over more extensive regions in Asian in previous studies. Thus, it is necessary to further study the impact and underlying physical mechanisms of the early and late BoBSM onset on Asian precipitation in May.

The remainder of this paper is organized as follows. In Sect. 2, we describe the data and methods used in this study. In Sect. 3, we examine the relationship between the BoBSM onset dates and Asian precipitation in May. In Sect. 4, we analyze atmospheric circulation anomalies affecting Asian precipitation and their possible causes. A summary of the results is provided in Sect. 5.

2 Data and methodology

In the present study, three precipitation datasets are used: version 2.2 of monthly precipitation from the Global Precipitation Climatology Project (GPCP) (Adler et al. 2003), monthly precipitation data from the National Oceanic and Atmospheric Administration (NOAA) PRECipitation REConstruction over Land (PREC/L) (Chen et al. 2002), and monthly data from 572 stations provided by the Chinese Meteorological Data Center. Daily and monthly atmospheric fields are taken from the second version of the National Center for Environmental Prediction–National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Kanamitsu et al. 2002). Daily and monthly NOAA Outgoing Longwave Radiation (OLR) is provided by the Climate Diagnostics Center (CDC) (Liebmann and Smith 1996). Global monthly SST data are from version 3b of the Extended Reconstruction SST (ERSST) (Smith et al. 2008). All data used in this study cover the period 1979–2013.

Zonal wind index (Jiang 2011) is used to characterize the interannual variation of the BoBSM onset in this study. Based on the 925 hPa zonal wind, the BoBSM onset date is defined as the first day after April 1 on which the average 925 hPa zonal wind over 80°–95°E, 2.5°–10°N (U) is more than 3.0 m s^{-1} in the following 7 days (including the onset day). The SCSSM onset date is defined by the first pentad that satisfies the following two criteria (Xie and Dai 2001): (a) the areal average zonal wind at 850 hPa over 105°–120°E and 5°–15°N (U_{SCS}) is more than 0 m s^{-1} in the onset pentad; (b) positive U_{SCS} must last for at least 2 pentads (including the onset pentad). Dates of summer monsoon onset over Kerala (MOK) are derived from Indian Meteorological Department (IMD).

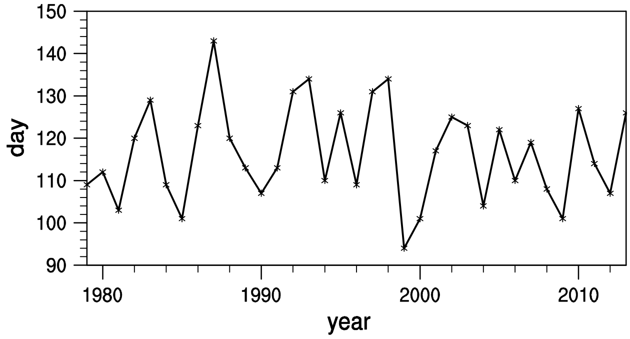

Fig. 1 Time series of the BoBSM onset dates defined by the U index. All dates are Julian days in the calendar year

The method used to locate the subtropical high ridge was elaborated by Li and Chou (1998) and Zhan et al. (2005). The characteristic line with $u = 0$, $\partial u/\partial y > 0$ over subtropical areas is used to identify the subtropical zonal ridge.

The apparent heat source Q_1 (Yanai et al. 1973, 1992) is defined by

$$Q_1 = C_p\left(p/p_0\right)^k\left(\partial\theta/\partial t + V\cdot\nabla\theta + \omega\partial\theta/\partial p\right), \qquad (1)$$

where θ is the potential temperature, V is the horizontal velocity, ω is the vertical p-velocity, and p is the pressure. In the equation $k = R/C_p$, where R and C_p are the gas constant and the specific heat at constant pressure of dry air, respectively, $p_0 = 1000$ hPa, and ∇ is the isobaric gradient operator. Atmospheric heat sources of the whole atmosphere column could be obtained by integrating Eq. (1) from the tropopause (taken as 100 hPa) to the surface (1000 hPa).

3 Relationship between the BoBSM onset date and Asian precipitation in May

3.1 Interannual variability of the BoBSM onset

Figure 1 show BoBSM onset dates for each individual year, based on the U index defined in the previous section. Interannual BoBSM onset dates differ significantly, with the range between the earliest and latest onset dates exceeding 1 month (Fig. 1). The climatological mean onset date is April 26, with a standard deviation of 12 days. Our result is consistent with previous results, despite slight differences in indices used in these studies (e.g., Mao and Wu 2007; Xing and Huang 2013).

The result indicates that U index is effective in characterizing the interannual variation of the BoBSM onset, and then the index is used to analyze the relationship between BoBSM onset dates and precipitation.

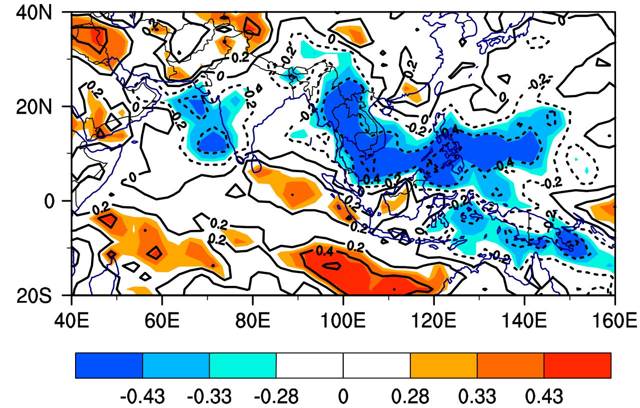

Fig. 2 Correlation between time series of dates of the BoBSM onset and precipitation in May. Negative contours are in *broken lines*. The *colors shadings* from *light* to *dark* indicate the 90, 95 and 99 % confidence levels according to a student's *t* test

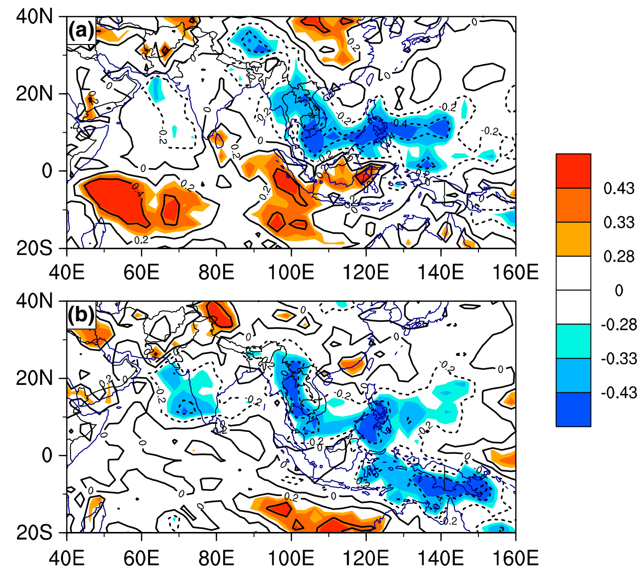

Fig. 3 **a** Correlation between the time series of the previous winter Niño 3 index and precipitation in May, and **b** partial correlations between the time series of BoBSM onset dates and precipitation in May, after removing the effects of the previous winter ENSO index. Negative contours are in *broken lines*. The *color shadings* from *light* to *dark* indicate the 90, 95 and 99 % confidence levels according to a student's *t*-test

3.2 Correlation between BoBSM onset dates and Asian precipitation in May

Figure 2 displays spatial distributions of the correlation coefficients between the BoBSM onset dates defined by the

U index and precipitation in May. Correlation coefficients over the colored areas are statistically significant, but weak to moderate (exceeding 0.28 or less than −0.28). It is seen that significant negative correlations between the U index and precipitation are observed over the southern Indian peninsula (SIP), Indochinese peninsula (ICP), southwest China (SWC) and the SCS to the east of the Philippines, while significant positive correlations are found over south China (SC) (Fig. 2).

Considering that ENSO is a very strong interannual signal and has a remote influence on other regions (e.g., Ropelewski and Halpert 1987; Wang et al. 2000; Feng and Li 2011), Fig. 3a shows correlations between the winter ENSO index and precipitation in May. Significant correlations in the tropics are distributed over the ICP and the southern SCS to the east of the Philippines, while little significant correlations are distributed over the SIP and SC. Upon comparison of Figs. 2 and 3a, it is clear that the significant correlation signal over the SIP and SC in Fig. 2 does not originate directly from ENSO. Furthermore, as ENSO and the BoBSM onset show some covariability (Mao and Wu 2007), partial correlation is used to exclude the possible effects of ENSO. Areas of significant correlation decrease after removing the previous winter ENSO signal, but the spatial distributions in Fig. 3b are very close to that in Fig. 2, confirming that the relationship between the early and late BoBSM onset and May rainfall in Asia doesn't completely depend on the ENSO. Moreover, we obtain similar results (figures not shown) using the PREC/L dataset (Chen et al. 2002).

To further identify the relationship between the BoBSM onset and precipitation in China, correlations between BoBSM onset dates defined by the U index and observed precipitation in China are shown in Fig. 4. The main region of significantly negative correlation is located in SWC. This is consistent with the above result (Fig. 2) and previous studies that show that the BoBSM activity affects Yunnan precipitation in May (Yan et al. 2003). The main region with significant positive correlations is observed over SC (Fig. 4), again in agreement with the results in Fig. 2.

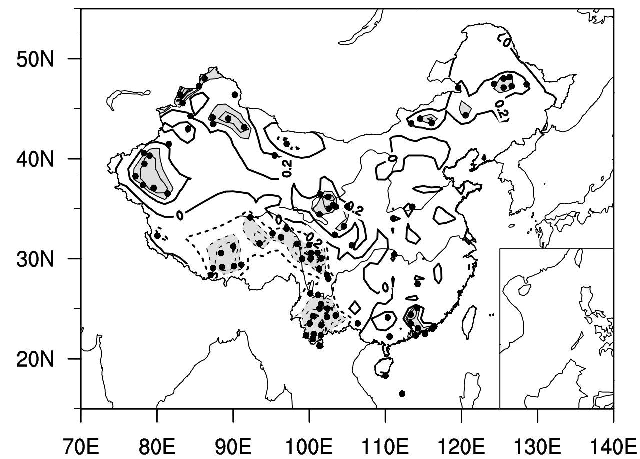

Fig. 4 Correlation between the time series of BoBSM onset and precipitation over China in May based on station data. Negative contours are in *broken lines*. The *shading* and *marked stations* indicate correlations significant at the 90 % confidence level according to a student's *t*-test

4 Atmospheric circulation anomalies affecting Asian precipitation and the possible causes

To examine circulation anomalies responsible for the linkage between the BoBSM onset and Asian precipitation, composite analyses are made for early and late onset years. Years of earlier and later BoBSM defined as years when the anomaly of the BoBSM onset date is less than one negative standard deviation or greater than one positive standard deviation, respectively. Figure 5 shows the composite in 850 hPa winds and vertical velocity in May during the earlier and later BoBSM years and the composite difference with respect to the U index. When the BoBSM occurs earlier (later), anomalous cyclonic (anticyclonic) circulation in the lower troposphere is present over the northwest of the BoB, SCS and Arabian Sea, respectively, and anomalous low-level westerlies (easterlies) prevail in the equatorial Indian Ocean (IO) to the east of the Philippines. The results also clearly show that northeasterlies (southwesterlies) are found over SC, while northeasterlies (southwesterlies) and southwesterlies (northeasterlies) converge (diverge) toward (away from) the ICP in the lower troposphere (Fig. 5a, c, e). Furthermore, the composites in vertical velocity at 850 hPa based on the U index (Fig. 5b, d, f) show that, when the BoBSM occurs earlier (later), there is anomalous ascending (descending) flow in the SIP, the BoB, and the ICP to the east of the Philippines, accompanying anomalous descending (ascending) flow over the eastern part of the central Indian peninsula and SC in the lower troposphere.

Therefore, when the BoBSM starts earlier, anomalous cyclonic circulation over the Arabian Sea to the west of Indian peninsula enhances local westerly components, and weakens local northerly components (figures not shown). These westerlies and southwesterlies anomalies are favorable for the lower-tropospheric convergence over the SIP, and thus resulting in local heavy rainfall. Anomalous cyclonic circulation over the BoB corresponds well to local climatological winds, while the anomalous cyclonic circulation over the SCS is contrary to local climatologcial winds (figures not shown). Associated with cyclonic circulation anomalies over the BoB and SCS, anomalous low-level convergent wind and ascending flows induce vertical transport of moisture anomalies, leading to heavy rain over

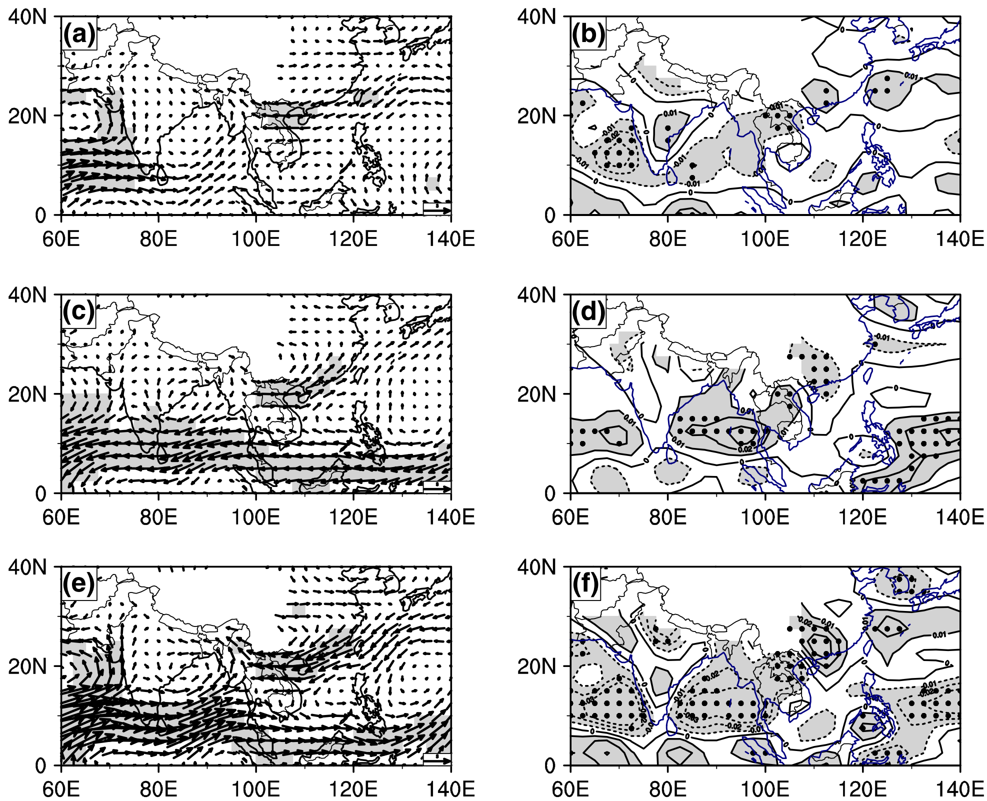

Fig. 5 Composite for **a**, **c** 850 hPa wind (m s^{-1}) and **b**, **d** vertical velocity (Pa s^{-1}) during earlier and later BoBSM onset years in May, and the composite differences in **e** 850 hPa wind (m s^{-1}) and **f** vertical velocity (Pa s^{-1}). Negative contours are in *broken lines* in **b**, **d**, **f**. The *shading* in **a**, **c** and **e** indicates significance at the 90 % confidence level from a student's *t*-test. The *shading* in **b**, **d** and **f** indicates areas of absolute vertical speed greater than 0.01 hPa s^{-1}, and the *black solid dots* indicate significance at the 90 % confidence level according to a student's *t*-test

the ICP and SCS, and anomalous southeasterlies transport more water vapor to SWC. Moreover, low-level northeasterlies and descending flow anomalies reduce moisture transport into SC where precipitation decreases, and vice versa.

In addition to the circulation anomalies in the lower troposphere, there is significant interannual variation of the subtropical highs in the middle troposphere. We measure the subtropical highs by the contour lines for 5870 or 5875 gpm (owing to differences in intensity for different cases) and zonal ridgelines. As shown in Fig. 6, there are remarkable differences in extent of the WPSH and subtropical high in the Indian Ocean (IOSH) for earlier and later cases. When the BoBSM occurs earlier, both of the ranges become smaller as a whole as compared to the climatological mean. In zonal direction, the WPSH shifts eastward into the southern ICP from the eastern BoB, and the IOSH shifts westward into the Arabian Sea from the Indian peninsula. The northern flank of WPSH retreats southward from the north of Hainan Island, China (HIC) to the south. Meanwhile, the zonal ridge breaks and moves outwards the BoB as compared with the climatological mean (Fig. 6a). When the BoBSM occurs later, the zonal ridge even doesn't break over the BoB. Meanwhile, the WPSH and IOSH enlarge, strengthen and extended towards the BoB as compared to the climatological mean (Fig. 6b), which show opposite variations to earlier cases. These changes are more favorable to cyclonic circulation anomalies over the Arabian Sea and SCS, and thus results in anomalous northeasterlies and descending flows over SC for earlier onset years (Fig. 5a, b), while the situation is reversed for later onset years (Fig. 5c, d).

How does the early and late BoBSM onset affect anomalous atmospheric circulation? Figure 7 shows composite patterns of SST anomalies (SSTA) for the early and late onset categories. When the BoBSM occurs earlier, there are significant negative anomalies in the tropical IO to the SCS; that is to say, SST is colder than the climatological mean (Fig. 7a, b). The opposite is true when the BoBSM occurs later (Fig. 7c, d). Atmospheric heating is closely to SSTA in tropics, and positive and negative heating induce cyclonic and anticyclonic circulation anomalies in the west region, respectively (e.g., Gill 1980; Yanai and Tomita 1998). Thus, negative (positive) SSTA from the tropical IO

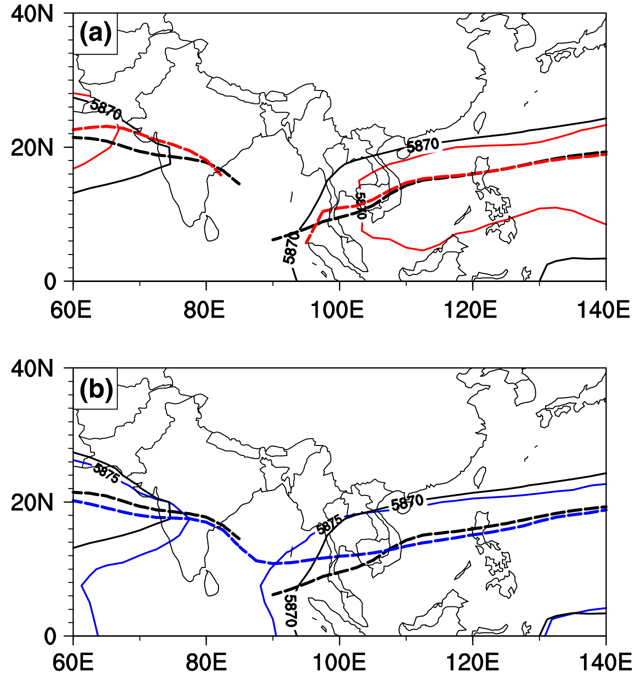

Fig. 6 *Contour lines* for 5870/5875 gpm (*solid lines*) and zonal ridgelines (*dashed lines*) for **a** earlier and **b** later BoBSM onset years in May. The *black colors* indicate the climatological mean, and the *red* and *blue colors* indicate the composite for earlier and later cases, respectively

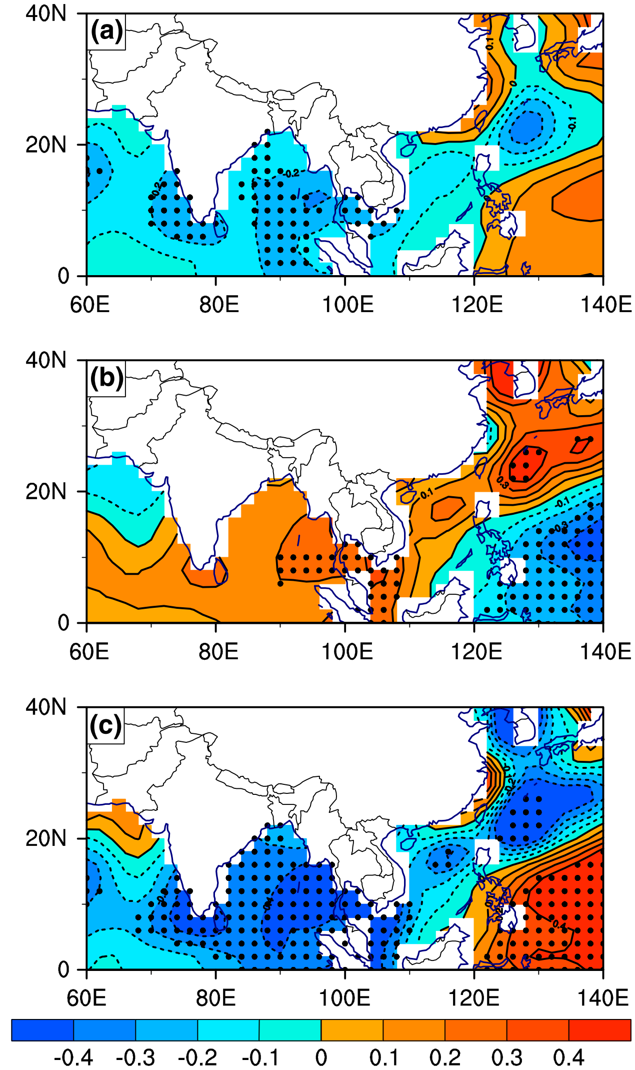

Fig. 7 Composite of SSTA (°C) in May for **a** earlier and **b** later BoBSM onset years and **c** the composite difference. Negative contours are in *broken lines*. The *black solid dots* indicate significance at the 90 % confidence level according to a student's *t*-test

to the SCS in early (late) BoBSM onsets are not consistent with anomalous cyclonic (anticyclonic) circulation. The result indicates the clue of low-level circulation variation in May isn't found through simultaneous SSTA.

However, regression distributions of OLR anomalies with respect to the BoBSM onset dates illustrate that in the early onset years, convective activity is relatively strong from the BoB to the SCS and Arabian Sea, while it is relatively weak in SC in May. The situation is reversed for late onset years (Fig. 8). Convective activities are closely related to the atmospheric heating; its enhancement could strengthen such heating, and atmospheric heating is the driving force of atmospheric circulation (Wang and Qian 2000). The theoretical analysis of Gill (1980) and Xing et al. (2014) explains that positive (negative) heat sources induce local low-level cyclonic (anticyclonic) circulation over the northwest of the heating and equatorial westerlies (easterlies). These are the same features seen over the BoB, SCS and Arabian Sea (Fig. 5), indicating that the anomalous convective activity associated with the early and late BoBSM onset influences circulation anomalies. Moreover, anomalous strong (weak) convective activities over the SCS and Arabian Sea correspond well to smaller (larger) extent of the WPSH and IOSH, respectively for earlier (later) onset years (Fig. 6).

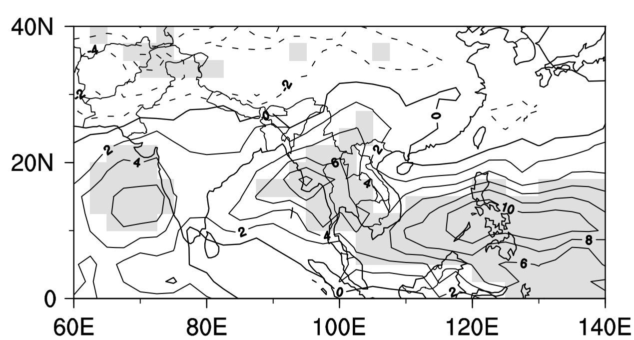

Fig. 8 Regression distribution of OLR with respect to BoBSM onset dates in May. Negative contours are in *broken lines*. The *shading* indicates significance at the 90 % confidence level from the student's *t*-test

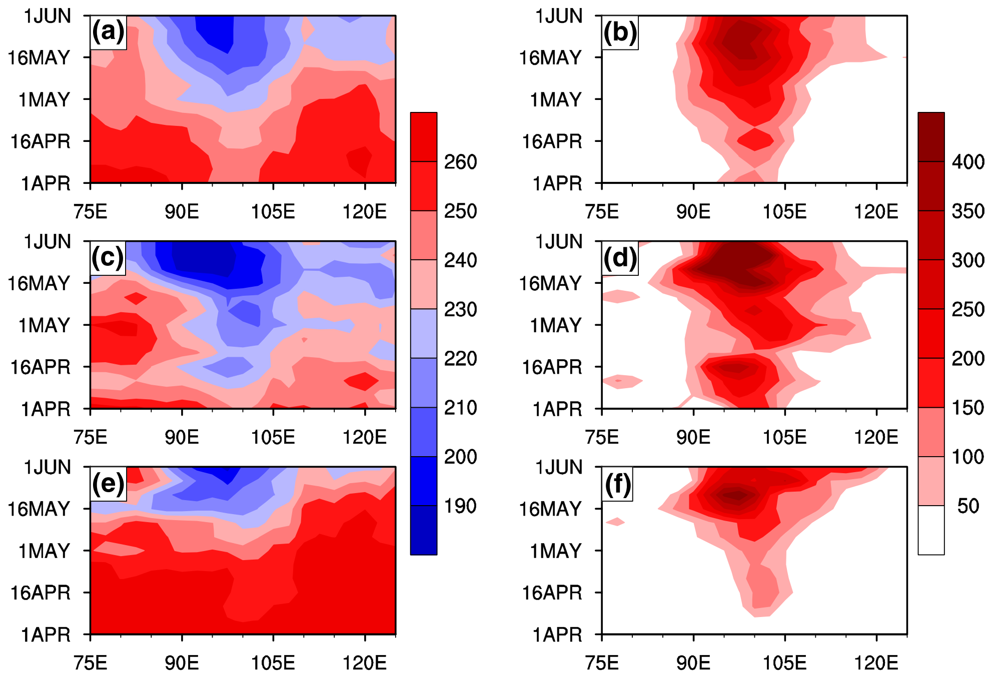

Fig. 9 Composite evolution of (*left column*) meridionally averaged (5°–15°N) OLR (W m^{-2}) and (*right column*) vertically integrated apparent heat sources (W m^{-2}) from 1000 to 100 hPa for **a**, **b** the climatological mean, **c**, **d** earlier BoBSM onset years, and **e**, **f** later BoBSM onset years based on U index during April and May

How does the convective activity in the BoB after the BoBSM onset affect convective activity over the SCS and Arabian Sea, and then influence local atmospheric circulation over both sides? Figure 9 shows the evolution of meridionally averaged (5°–15°N) OLR and vertically integrated apparent heat sources from 1000 to 100 hPa gotten by Eq. (1) for the climatological, early, and late BoBSM onset cases. In the climatological average shown in Fig. 9a, b convective activity gradually strengthens and apparent heat sources gradually increase before the BoBSM onset. The OLR value drops below the critical value of 230 W m^{-2} in the BoB in late April, indicating the earliest onset of the monsoon (e.g., Mao and Wu 2007). Associated with the BoBSM onset, atmospheric heating significantly increases over the BoB. Due to all-area development of strong convective activities in the BoB after the BoBSM onset, heating in the BoB shows westward spread. Meanwhile, it also propagates eastward to the SCS in association with the southwesterlies in the lower and middle troposphere after the BoBSM onset. Thus, the spread of heating towards both sides makes the WPSH and IOSH retreat, and weakens local subtropical high (e.g., Liu et al. 1999; Zhang et al. 2002a). For earlier cases, strong convective activities and heating emerge in the BoB in middle April, and atmospheric heating in the BoB spreads earlier towards both sides (Fig. 9c, d). Earlier spread of heating in the BoB since the middle April results in earlier retreat of the WPSH and IOSH outwards the BoB (e.g., Liu et al. 1999; Zhang et al. 2002a), and thus the WPSH and IOSH present larger retreat outwards the BoB and smaller meridional extent over the SCS and Arabian Sea in May (Fig. 6a), which results in anomalous positive heating over the SCS and Arabian Sea (Fig. 8). The situation for convective activities and heating is reversed for later cases (Fig. 9e, f). Later spread of atmospheric heating leads to smaller retreat of the WPSH and IOSH outwards the BoB in May (Fig. 6b), and thus leading to negative heating anomalies over the SCS and Arabian Sea (Fig. 8).

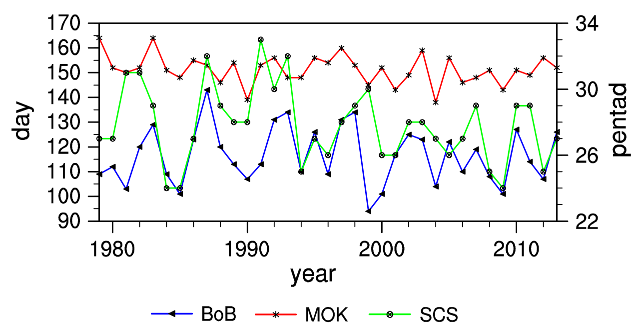

Fig. 10 Time series of BoBSM onset dates defined by the U index (*blue line*, unit: day), the SCSSM onset defined by the U_{SCS} index (*green line*, unit: pentad), and the monsoon onset over Kerala (*red line*, unit: day)

Moreover, time series of the BoBSM and SCS summer monsoon (SCSSM) onset dates in Fig. 10 show significantly interannual variation, while the SCSSM onset shows an interdecadal change around 1993 (Kajikawa and Wang 2012; Kajikawa et al. 2012). The climatological mean onset dates of the BoBSM and SCSSM are the 24th and 28th pentad, respectively, and the result is consistent with previous results (e.g., Zhang et al. 2002b; Wang et al. 2004). The correlation coefficient between dates of the BoBSM and SCSSM onset is 0.43, and exceeds the 99 % confidence level. Moreover, it is found that there also exists significant positive correlation (0.57, exceeding the 99 % confidence level) after removing the interdecadal variation (9-year filter) from the original BoBSM and SCSSM onset dates. The result further indicates that, on interannual scales, atmospheric heating induced by local convective activity over the BoB spreads eastward to the SCS after the BoBSM onset, affecting local evolution of low-level circulation and summer monsoon onset over the SCS. Meanwhile, the BoBSM onset has significantly positive correlation (0.42, exceeding the 99 % confidence level) with the MOK (Fig. 10), supporting that the impact of the early and late BoBSM onset on SIP precipitation by affecting local evolution of SIP circulation on interannual scale.

5 Summary and discussion

In the present study, the impact of early and late BoBSM onset on Asian precipitation in May has been examined. When the BoBSM occurs earlier (later), there is more (less) precipitation in the SIP, the ICP, SWC, and the SCS and less (more) precipitation in SC in May.

Figure 11 shows a schematic of the processes of the impact of earlier and later BoBSM onset on May rainfall over Asia. When the BoBSM occurs earlier than the climatological mean (late April), strong convective activity and heating occurs earlier over the BoB, which causes local positive heating anomalies in May. Then the WPSH and IOSH retreat earlier outwards the BoB, owing to earlier spread of heating towards both sides. Thus, the two subtropical highs show larger retreat outwards the BoB and smaller merdional extent over the SCS and Arabian Sea in May. It is obvious that the WPSH shifts eastward into the southern ICP from the eastern BoB, and the IOSH shifts westward into the Arabian Sea from the Indian peninsula for earlier cases in May. The northern flank of the WPSH moves southwards from the north of HIC to the south as compared to the climatological mean. Changes of the two subtropical highs contribute to positive heating anomalies over the SCS and Arabian Sea. Thus cyclonic circulation anomalies in the lower troposphere are excited by positive heating anomalies over the BoB, SCS and Arabian Sea, accompanying with anomalous ascending flows over the tropical IO to the east of the Philippines and anomalous descending flows over the eastern part of the central Indian peninsula and SC in the lower troposphere. These anomalous circulation patterns favor positive precipitation anomalies over the SIP, ICP, SWC, and the SCS and negative rainfall anomalies over SC. The situation is reversed for a later BoBSM onset.

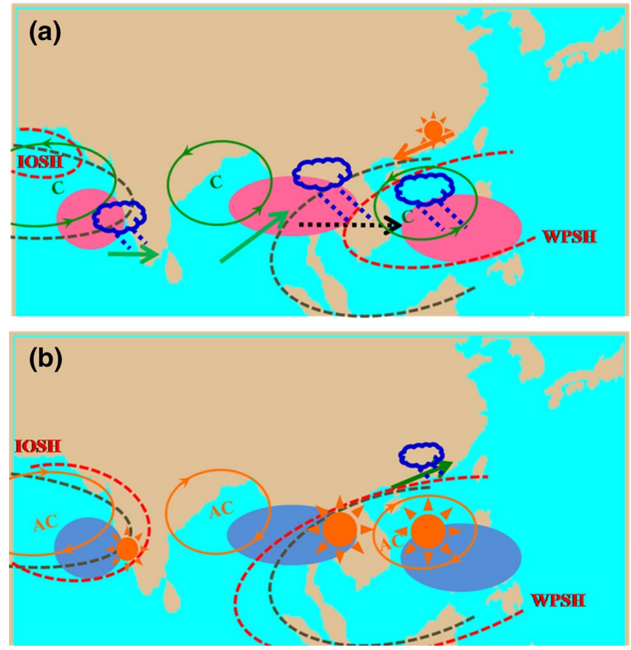

Fig. 11 Schematic showing the processes of the impact of **a** earlier and **b** later BoBSM onset on Asian precipitation in May. *Pink* and *blue shadings* indicate anomalous heating and cooling, respectively; the *blue clouds* show positive precipitation anomalies; and *green* and *orange arrows* represent anomalous westerlies/southwesterlies and northeasterlies at 850 hPa, respectively. The *dashed dark brown* (*red*) *lines* represent the IOSH and the WPSH at 500 hPa for the climatological mean (earlier and later onset years), respectively. The *dashed black line* represents the eastward spread of enhanced heating, and “C” and “AC” indicate anomalous cyclonic and anticyclonic circulation at 850 hPa, respectively

In this study, we investigated the impact of the early and late BoBSM onset on precipitation over Asia, and the subsequently notable issue is on the cause of the interannual variation of the BoBSM onset dates. Previous studies indicated that factors responsible for the interannual variation of the BoBSM onset include thermal condition (Wu and Zhang 1998) and snow cover over the Tibetan Plateau (Mao and Wu 2007), the south Asian high establishment over the Indo-China peninsula (Wang and Guo 2012), the tropical western Pacific Ocean (Feng et al. 2013), ENSO (Mao and Wu 2007; Wang et al. 2013), local SST (Jiang and Li 2011; Yu et al. 2012) and so on. Among them, Jiang and Li (2011) indicated that the annual SST cycle involves a shift in the warmest SST axis (WSSTA) from the equator to the central

BoB, and this northward jump leads the monsoon onset by two pentads. The result provides a possible predictor for the BoBSM onset, and the issue should be addressed in future.

Acknowledgments We sincerely thank two anonymous referees whose comments improved the paper. This study was supported by the National Natural Science Foundation of China (Grant No. 41375110), by the State Key Program of National Natural Science of China (Grant No. 41030961), by the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant No. XDA05090403) and by the 973 Program (2013CB430200).

Compliance with ethical standards

Conflict of interest Nan Xing, Jianping Li and Lanning Wang declare that they have no conflicts of interest regarding the publication of this paper.

References

Adler RF et al (2003) The version-2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis (1979–present). J Hydrometeor 4:1147–1167

Chen M, Xie P, Janowiak JE, Arkin PA (2002) Global land precipitation: a 50-yr monthly analysis based on gauge observations. J Hydrometeor 3:246–266

Chen Y, Ding Y, Xiao Z, Yan H (2006) The impact of water vapor transport on the summer monsoon onset and abnormal rainfall over Yunnan province in May (in Chinese). Chinese J Atmos Sci 30:25–37

Feng J, Li JP (2011) Influence of El Niño Modoki on spring rainfall over south China. J Geophys Res. doi:10.1029/2010JD015160

Feng J, Hu D, Yu L (2013) Role of Western Pacific Oceanic variability in the onset of the Bay of Bengal summer monsoon. Adv Atmos Sci 30:219–234

Gill AE (1980) Some simple solutions for heat-induced tropical circulation. Q J R Meteorol Soc 106:447–462

Hsu H-H, Terng C-T, Chen C-T (1999) Evolution of large-scale circulation and heating during the first transition of Asian summer monsoon. J Clim 12:793–810

Huang R, Huang G, Wei Z (2004) Climate variations of the summer monsoon over China. In: Chang C (ed) The East Asian Monsoon. World Scientific, Singapore, pp 213–268

Jiang X (2011) Air-sea interactions during monsoon onset over the Bay of Bengal. Dissertation, Lanzhou University

Jiang X, Li JP (2011) Influence of the annual cycle of sea surface temperature on the monsoon onset. J Geophys Res. doi:10.1029/2010JD015236

Kajikawa Y, Wang B (2012) Interdecadal Change of the South China Sea Summer Monsoon Onset. J Clim 25:3207–3218. doi:10.1175/Jcli-D-11-00207.1

Kajikawa Y, Yasunari T, Yoshida S, Fujinami H (2012) Advanced Asian summer monsoon onset in recent decades. Geophys Res Lett. doi:10.1029/2011GL050540

Kanamitsu M, Ebisuzaki W, Woollen J, Yang S-K, Hnilo J, Fiorino M, Potter G (2002) NCEP–DOE AMIP-II reanalysis (R-2). Bull Am Meteor Soc 83:1631–1643

Krishnamurthy V, Shukla J (2000) Intraseasonal and interannual variability of rainfall over India. J Clim 13:4366–4377

Lau K, Yang S (1997) Climatology and interannual variability of the Southeast Asian summer monsoon. Adv Atmos Sci 14:141–162

Li JP, Chou J (1998) The Qualitative Theory on the dynamical equations of atmospheric motion and its applications (in Chinese). Chin J Atmos Sci 22:348–360

Li C, Qu X (2000) Large Scale atmospheric circulation evolutions associated with summer monsoon onset in the South China Sea. Chin J Atmos Sci 24:1–14

Li JP, Zeng Q (2002) A unified monsoon index. Geophys Res Lett. doi:10.1029/2001GL013874

Li JP, Zhang L (2009) Wind onset and withdrawal of Asian summer monsoon and their simulated performance in AMIP models. Clim Dyn 32:935–968. doi:10.1007/s00382-008-0465-8

Liebmann B, Smith CA (1996) Description of a complete (interpolated) outgoing longwave radiation dataset. Bull Amer Meteor Soc 77:1275–1277

Liu Y, Ding Y (2008) Teleconnection between the Indian summer monsoon onset and Meiyu over the Yangtze River, China. Sci China Earth Sci 38:763–775

Liu Y, Wu G, Liu H, Liu P (1999) The effect of spatially nonuniform heating on the formation and variation of subtropical high part: condensation heating and south Asia high and western Pacific subtropical high (in Chinese). Acta Meteor Sin 57:525–538

Liu Y, Chan JC, Mao J, Wu G (2002) The role of Bay of Bengal convection in the onset of the 1998 South China Sea summer monsoon. Mon Weather Rev 130:2731–2744

Lu E, Chan JC (1999) A unified monsoon index for South China. J Clim 12:2375–2385

Mao J, Wu G (2007) Interannual variability in the onset of the summer monsoon over the Eastern Bay of Bengal. Theor Appl Climatol 89:155–170. doi:10.1007/s00704-006-0265-1

Mao J, Wu G, Liu Y (2002a) Study on modal variation of subtropical high and its mechanism during seasonal transition Part I: climatological features of subtropical high structure (in Chinese). Acta Meteor Sin 60:400–408

Mao J, Wu G, Liu Y (2002b) Study on modal variation of subtropical high and its mechanism during seasonal transition Part II: seasonal transition index over Asian monsoon region (in Chinese). Acta Meteor Sin 60:409–420

Pai D, Nair RM (2009) Summer monsoon onset over Kerala: new definition and prediction. J Earth Syst Sci 118:123–135

Ropelewski CF, Halpert MS (1987) Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation. Mon Weather Rev 115:1606–1626

Saini R, Barlow M, Hoell A (2011) Dynamics and thermodynamics of the regional response to the Indian monsoon onset. J Clim 24:5879–5886

Smith TM, Reynolds RW, Peterson TC, Lawrimore J (2008) Improvements to NOAA's historical merged land-ocean surface temperature analysis (1880–2006). J Clim 21:2283–2296. doi:10.1175/2007JCLI2100.1

Tamura T, Koike T (2010) Role of convective heating in the seasonal evolution of the Asian summer monsoon. J Geophys Res. doi:10.1029/2009JD013418

Tao S, Chen L (1988) A review of recent research on the East Asian Summer monsoon in China. In: Tao S (ed) Monsoon meteorology. Oxford University Press, Oxford, pp 60–92

Wang Q, Ding Y (1997) Climatological aspects of evolution of summer monsoon over the northern South China Sea. Acta Meteor Sin 55:466–483

Wang L, Guo S (2012) Interannual variability of the South-Asian high establishment over the Indo-China Peninsula from April to May and its relation to southern Asian summer monsoon. Trans Atmos Sci 35:10–23

Wang B, LinHo (2002) Rainy season of the Asian-Pacific summer monsoon. J Clim 15:386–398

Wang S, Qian Y (2000) Diagnostic study of apparent heat sources and moisture sinks in the South China Sea and its adjacent areas during the onset of 1998 SCS monsoon. Adv Atmos Sci 17:285–298

Wang B, Wu R, Fu X (2000) Pacific-East Asian teleconnection: how does ENSO affect East Asian climate? J Clim 13:1517–1536

Wang B, Zhang Y, Lu M (2004) Definition of South China Sea monsoon onset and commencement of the East Asia summer monsoon. J Clim 17:699–710
Wang X, Jiang X, Yang S, Li Y (2013) Different impacts of the two types of El Nino on Asian summer monsoon onset. Environ Res Lett. doi:10.1088/1748-9326/8/4/044053
Webster PJ, Yang S (1992) Monsoon and ENSO: selectively interactive systems. Q J R Meteorol Soc 118:877–926
Webster PJ, Magana VO, Palmer T, Shukla J, Tomas R, Yanai M, Yasunari T (1998) Monsoons: processes, predictability, and the prospects for prediction. J Geophys Res 103:14451–14510
Wu G, Zhang Y (1998) Tibetan Plateau forcing and the timing of the monsoon onset over South Asia and the South China Sea. Mon Weather Rev 126:913–927
Xie A, Dai N (2001) Elementary comment on South China Sea onset date and monsoon intensity. In: Gao H, HE J, Ding Y (eds) Determination of South China Sea summer monsoon onset date and monsoon index. China Meteorological Press, Beijing, pp 67–70
Xing W, Huang F (2013) Definition and interannual variability of the eastern Bay of Bengal summer monsoon onset. Period Ocean Univ China 43:1–8
Xing N, Li JP, Li Y (2014) Response of the tropical atmosphere to isolated equatorial asymmetric heating (in Chinese). Chin J Atmos Sci 38:1147–1158
Yan H, Xiao Z, Wang L (2003) Activities of Bay of Bengal monsoon and beginning date of rain season in Yunnan (in Chinese). Plateau Meteorol 22:624–630
Yanai M, Tomita T (1998) Seasonal and interannual variability of atmospheric heat sources and moisture sinks as determined from NCEP-NCAR reanalysis. J Clim 11:463–482
Yanai M, Esbensen S, Chu J-H (1973) Determination of bulk properties of tropical cloud clusters from large-scale heat and moisture budgets. J Atmos Sci 30:611–627
Yanai MH, Li CF, Song ZS (1992) Seasonal heating of the Tibetan Plateau and its effects on the evolution of the Asian summer monsoon. J Meteor Soc Japan 70:319–351
Yu W, Shi J, Liu L (2012) The onset of the monsoon over the Bay of Bengal: the observed common features for 2008–2011. Atmos Oceanic Sci Lett 5:314–318
Zhan R, Li JP, He J (2005) Statistical characteristics of the double ridges of subtropical high in the Northern Hemisphere. Chinese Sci Bull 50:2336–2341
Zhang L, Li JP (2008) Seasonal rotation features of wind vectors and application to evaluate monsoon simulations in AMIP models. Clim Dyn 31:417–432
Zhang Y, Li T, Wang B, Wu G (2002a) Onset of the summer monsoon over the Indochina Peninsula: climatology and interannual variations. J Clim 15:3206–3221
Zhang X, Li J, Yan J, Ding Y (2002b) A study of circulation characteristics and index of the South China Sea summer monsoon. Climatic Environ Res 7:321–331