ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 20, NO. 5, 2003, PP. 781–793

30–60-day Oscillations of Convection and Circulation Associated with the Thermal State of the Western Pacific Warm Pool during Boreal Summer

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(Received 9 August 2002; revised 13 May 2003)

ABSTRACT

This study focuses on the characteristics of the 30–60-day oscillation (MJO) associated with the interannual variability of the thermal state in the western Pacific warm pool. The composite results show that the amplitude of MJO convection over the tropical western Pacific tends to intensify (reduce) in the WARM (COLD) case. The negative correlations between MJO convection in the WARM and in the COLD cases are examined to be significant over most of the Asian-Pacific region. The evolutions of MJO convection and lower circulation, on the one hand, exhibit larger differences between the WARM and COLD cases, but on the other hand, display a unique feature in that a well-developed MJO cyclone (anticyclone) is anchored over the Asian-Western Pacific domain at the peak enhanced (suppressed) MJO convection phase over the western Pacific warm pool, either in the WARM or in the COLD case. This unique feature of MJO shows a Gill-type response of lower circulation to the convection and is inferred to be an inherent appearance of MJO. The context in the paper suggests there may exist interactions between MJO and the interannual variability of the thermal state in the western Pacific warm pool.

Key words: 30–60-day oscillation, western Pacific warm pool, thermal states，convection, circulation

1. Introduction

Following Madden and Julian's pioneering work (Madden and Julian, 1971, 1972), the 30–60-day intraseasonal oscillation has been a topic studied by many researchers for decades. The 30–60-day oscillation (or so-called MJO) is regarded as a dominant mode of variability in the tropics. It is manifested as large-scale eastward propagating circulation anomalies and associated convection anomalies (Knutson and Weickmann, 1987; Murakami and Nakazawa, 1985; and many others) and northward propagation over the Indian monsoon region (Yasunari, 1981; Krishnamurti and Subrahmanyam, 1982), and is associated with the active/break cycle of the Indian summer monsoon (Murakami et al., 1986; Lau and Chan, 1986). Some studies also have shown that it interacts with the midlatitudes (Lau and Phillips, 1986) and has a relationship with the South China Sea summer monsoon (Mu and Li, 2000; Li et al., 2001). Furthermore, the 30–60-day oscillation is phase-locked (Nakazawa, 1992; Wang and Xu, 1997). In addition, some works also have argued that the Madden-Julian Oscillation (MJO) or 30–60-day oscillation may be a coupled atmosphere-ocean phenomena (e.g., Flatau et al., 1997; Hendon and Glick, 1997; Woolnough et al., 2000). The sea surface temperature in the warm pool is modulated by the passages of MJO and the surface flux associated with it (e.g., Weller and Anderson, 1996; Lau and Sui, 1997). More recently, Woolnough et al. (2001) using a GCM model showed that the tropical convection of MJO could be organized by intraseasonal varying SSTs and the results were relevant to the observations. Since the regular occurrence of strong MJO over the western Pacific during the onset of El Niño events (e.g., Gutzler, 1991; Kessler and McPhaden, 1995; Verbickas, 1998), there have been a great number of papers contributing to the possibility of a physical connection between the

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two frequencies (Lau and Shen, 1988; Vincent et al., 1998; Li and Li, 1998; Slingo et al., 1999; Kessler and Kleeman, 2000; Chen et al., 2001). Nevertheless, the connection has been controversial because the indices of the prominent MJO signal show that interannual variabilities in overall MJO activity are not related to the ENSO cycle (Slingo et al., 1999; Hendon et al., 1999). Obviously, much work is still needed to probe into this problem.

On the other hand, the western Pacific warm pool is known as a key region in the global climate variability, whose thermal states and overlying convection greatly affect the interannual variations of the East Asian summer monsoon (Nitta, 1987; Huang and Li, 1987; Huang and Sun, 1992; Ren and Huang, 1999). The intraseasonal variability of the East Asian summer monsoon is closely associated with the 30–60-day oscillation in the tropical western Pacific (Huang, 1994). Whereas how the 30–60-day intraseasonal oscillation varies in association with the interannual variability of the thermal state in the western Pacific warm pool is still poorly understood. Since the intraseasonal variations include two dominant modes, the 10–25-day or bi-weekly oscillation and the 30–60-day or MJO oscillation, it is interesting to ask what is the relationship between these two frequencies and the thermal states in the western Pacific warm pool. In another paper, Ren and Huang (2002) discussed the characteristics of the 10–25-day oscillation. This paper therefore is dedicated to investigate the characteristics of convection and lower tropospheric circulation on the 30–60-day (MJO) timescale associated with extreme warm (and cold) thermal states in the western Pacific warm pool during boreal summer. The organization of the paper is as follows. Section 2 is the description of data and methods. The composite features of convection anomalies in the 30–60-day band are shown in section 3. Section 4 gives the results for 30–60-day oscillation space-time evolution of convection and lower circulation anomalies. A summary and discussion are presented in section 5.

2. Data and method

The satellite-observed Equivalent Temperature of Black Body at (TBB) at Cloud Top dataset compiled by the Japan Meteorology Agency is used as a proxy for convection in the study. The TBB records are gridded data with 1° × 1° resolution ranging from 1980 to 1997, which were originally observed at an interval of 3 hours each day. We have made daily TBB data by averaging these hourly data for each day. The NCEP/NCAR reanalysis daily, 2.5° × 2.5°, gridded wind dataset at 850 hPa for the same period as TBB is also utilized.

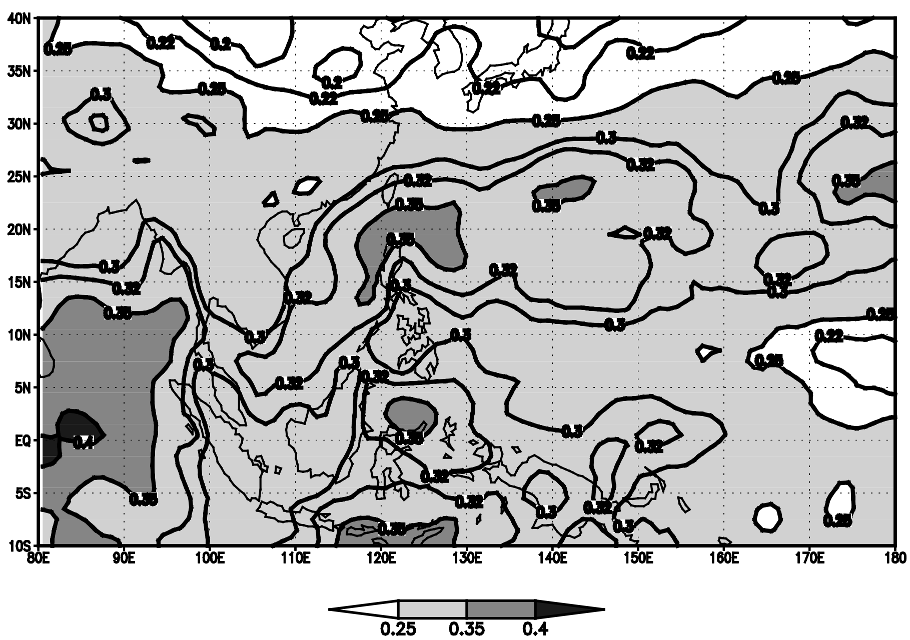

Fig. 1. The ratio of TBB MJO variances to the total daily variances averaged between 1 May to 30 September from 1980 to 1997. Values greater than 0.25 (i.e., 25%) are shaded.

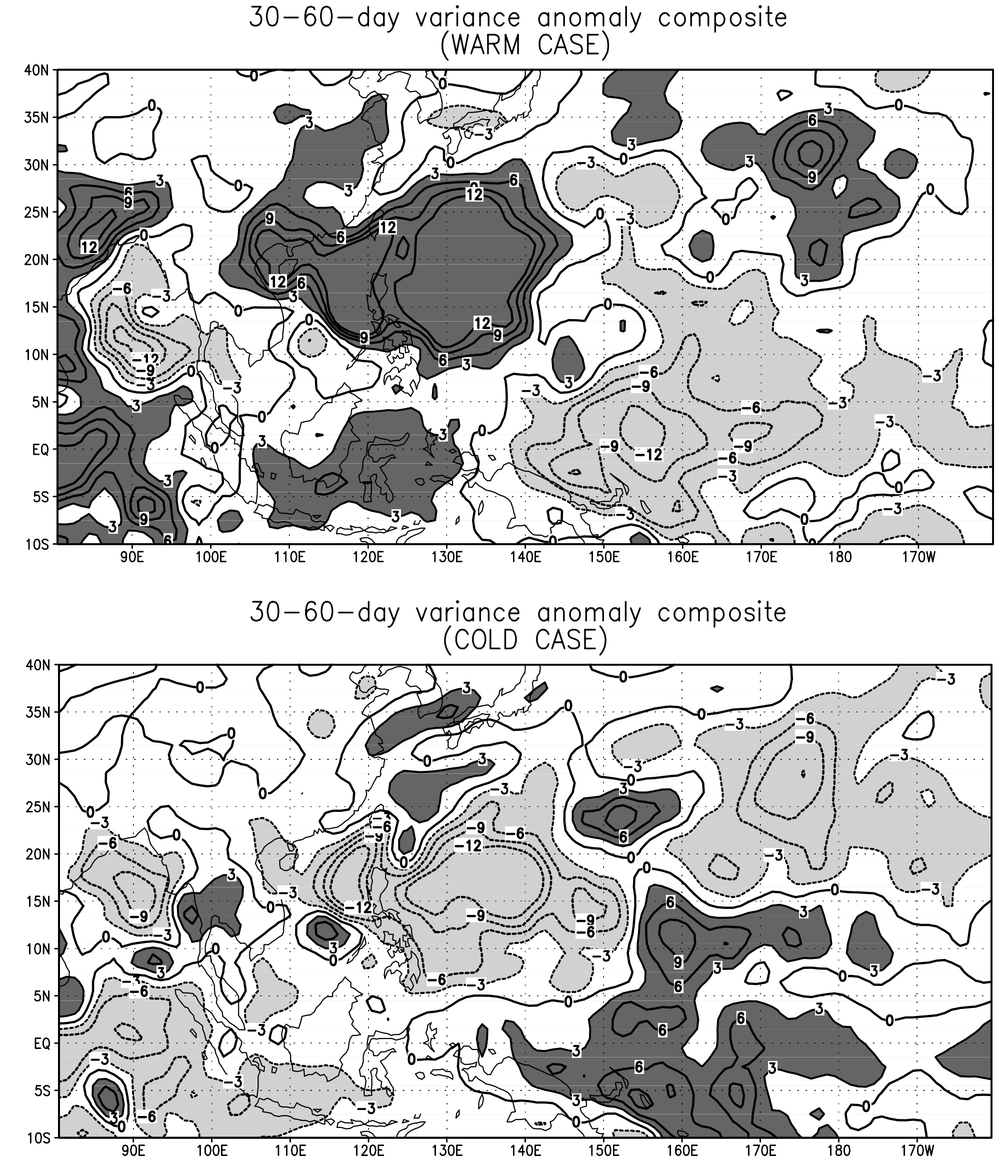

Fig. 2. Composite 30–60-day TBB variance anomalies in the WARM (upper panel) and COLD (lower panel) cases. Heavy shading denotes positive variance anomaly and light shading for negative.

In this study, we use an 18-year summer dataset, i.e., daily data from May to September. For these daily data (TBB and wind at 850 hPa), we first calculate their daily anomalies by subtracting them from their corresponding climatological daily mean. Then their seasonal trends are also removed by subtracting the quadratic trend at each grid point. Second, we apply a band-pass filter as in Murakami (1979) to these detrended daily anomalies to obtain their 30–60-day components for each summer. To show the robustness of MJO, we calculate the percentage of MJO variances to the total daily variances during the May to September period, as shown in Fig. 1. It is seen that MJO is predominant over most of the Asian-Pacific regions.

In the next sections, we will examine 30–60-day intraseasonal oscillations of convection and lower circulations for the warm and cold summers of the western Pacific warm pool (hereafter referred to as WARM, and COLD cases). The warm (cold) summers are 1981, 1984, 1988, 1995, and 1996 (1980, 1982, 1983, 1993, and 1997), which are the same as those used in Ren and Huang (2002). The analysis is then based upon the composite dataset that is obtained by averaging the corresponding warm (cold) summers′ 30–60-day filtered TBB and wind data. As a matter of fact, all

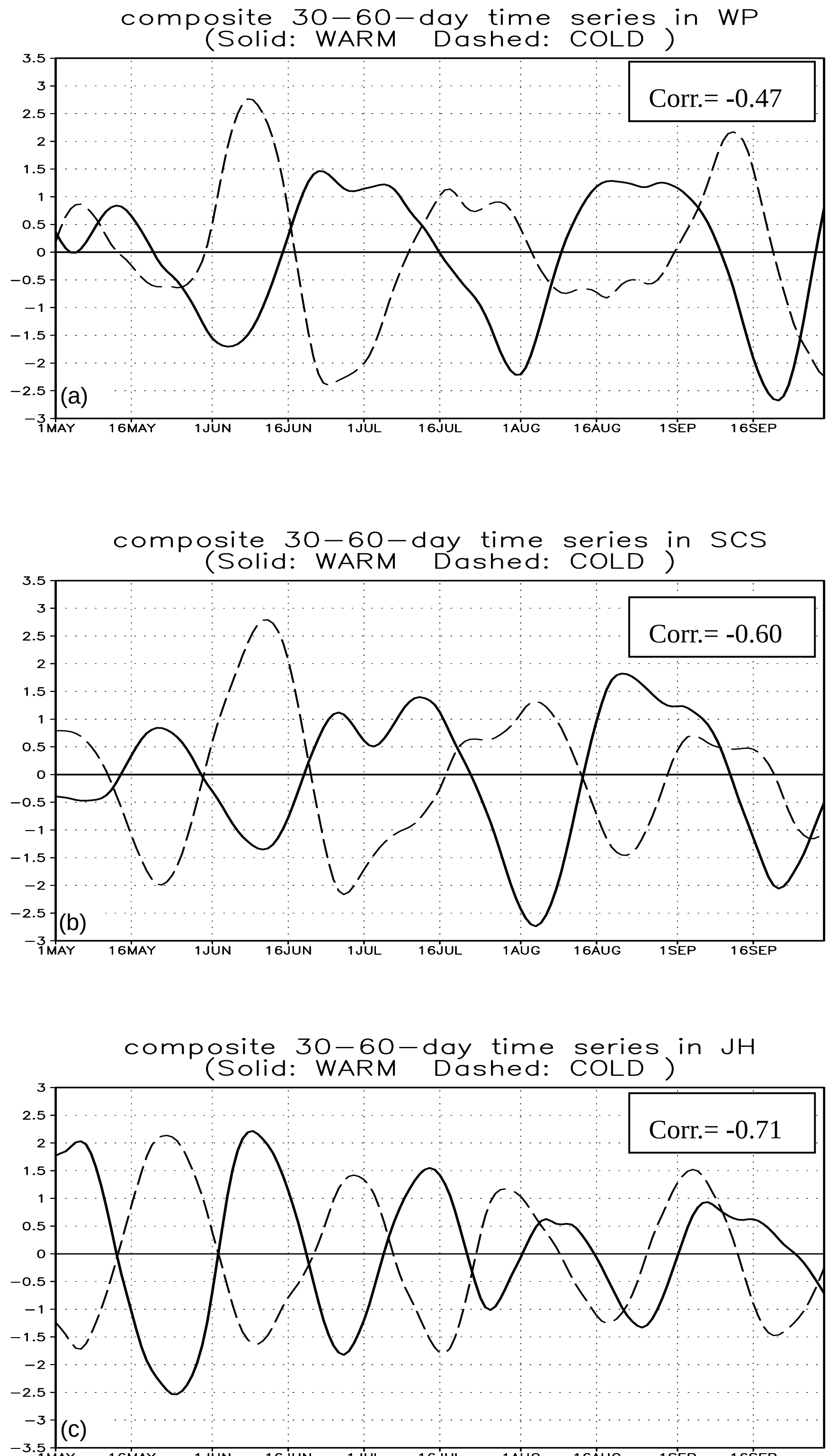

Fig. 3. Normalized time series of TBB 30–60-day anomaly in WARM (solid) and COLD (dashed) over (a) the tropical western Pacific, (b) the South China Sea, and (c) the Yangtze and Huaihe Rivers.

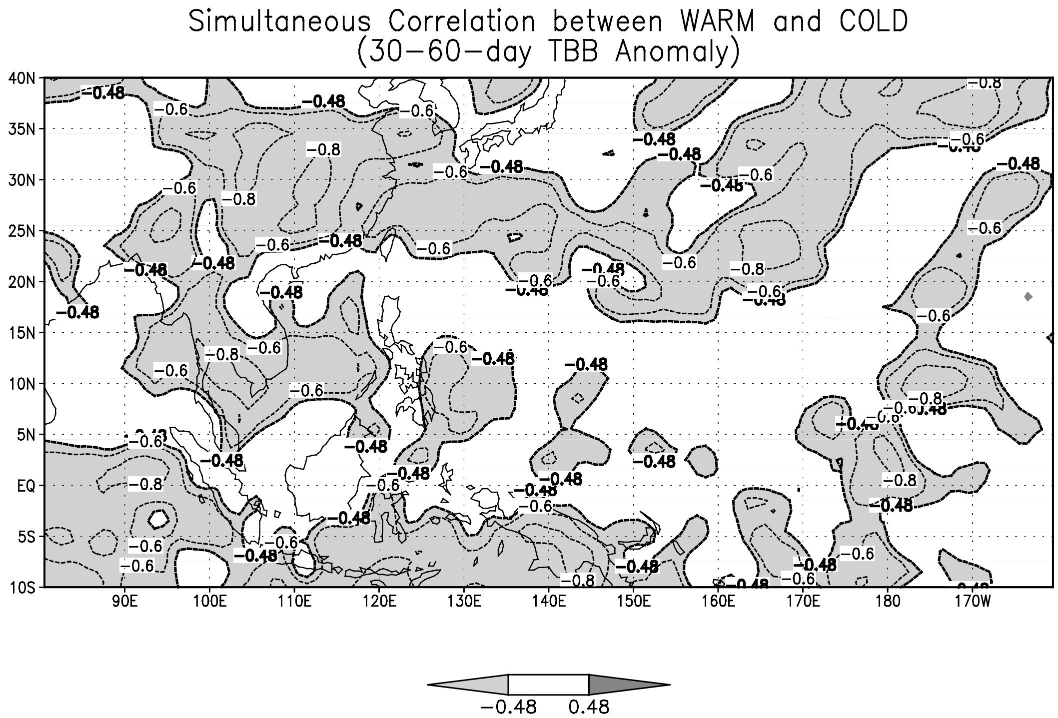

Fig. 4. Simultaneous correlation between WARM and COLD of TBB anomalies in the 30–60-day band from 1 May to 30 September. Shading denotes the correlation coefficient exceeding the 95% significance level.

data and processing techniques used in this paper are almost the same as in Ren and Huang (2002), except the bandpass filtering window here is 30–60-day.

3. Characteristics of 30–60-day convection anomalies

3.1 *Spatial distribution of 30–60-day TBB variances*

To detect the variability of the 30–60-day oscillation of convection, we will show the spatial distribution of the convection variance anomalies on this time band from May to September in the WARM and COLD cases, respectively. The variance for an individual year is defined as

$$\sigma^2_{\text{year}} = \sum_{n=1}^{153} \frac{[T_{\text{bb, year}}(n)]^2}{153} \, , \tag{1}$$

where T_{bb} is TBB. The subscript "year" is added to (1) to indicate that the 30–60-day bandpass-filtered TBB data in that year enter the formula. The climatological mean of 30–60-day convection variance is simply the arithmetical average through 1980 to 1997. Then the variance anomaly for each year is acquired by subtracting the climatological mean variance from that year's 30–60-day TBB variance.

Figure 2 shows the composite spatial distribution of the 30–60-day TBB variance anomalies in the WARM (upper panel) and COLD (lower panel) cases. When the thermal state over the western Pacific warm pool is warmer than normal (upper), TBB variance anomalies with 30–60-day oscillation are positive over the South China Sea and western Pacific around the Philippines indicating intensified convection amplitude

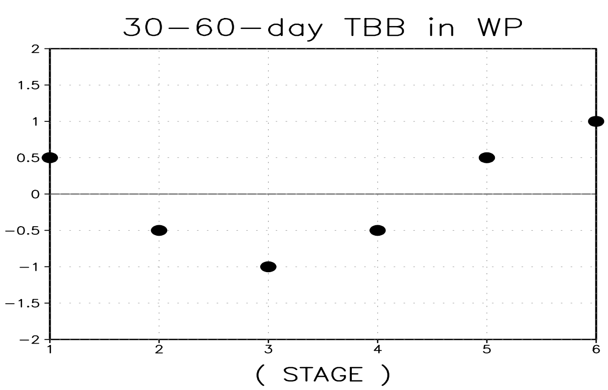

Fig. 5. Sketch map to show the stages for the composite. The y-axis denotes standard deviation of the 30–60-day TBB anomaly time series over the western Pacific warm pool (Fig. 3 upper panel).

of the 30–60-day oscillation. But the equatorial central and eastern Pacific show the obvious negative signature of 30–60-day TBB variance anomalies, implying convection amplitude there is weaker than normal. Furthermore, positive anomalies can be seen over the equatorial Indian Ocean. In the COLD case (lower panel), i.e., when the thermal state over the western Pacific warm pool is colder than normal, the distribution of variance anomalies of the 30–60-day convection is almost opposite to its counterpart in the upper panel.

3.2 *Temporal variability of the convection in the 30–60-day band*

In order to investigate the impact of the thermal state over the western Pacific warm pool on the phase of the 30–60-day convection oscillation, we show in Fig. 3 the realizations of 30–60-day TBB anomaly over three preferred regions, the tropical western Pacific (upper panel: 0°–14°N, 130°–150°E), the South China Sea (middle panel: 5°–20°N, 110°–120°E) and the East Asian monsoon region represented by the Yangtze River and Huaihe River (lower panel: 27°–34°N, 112°–122°E) in the WARM and COLD cases, respectively. The curves have been normalized by their corresponding standard deviations. Also shown in the figure is the simultaneous correlation coefficient between the time series in the WARM case and that in the COLD case from 1 May to 30 September for each of the three locations. Following Davis (1976), we have estimated an averaging threshold of 0.48 that is equivalent to a local 95% significance level. The convection anomalies over the three regions disclose a dominant negative relationship between the WARM and COLD cases in the 30–60-day band. This implies that this peculiar out-of-phase relationship between the WARM and COLD cases is probably due to the interannual thermal contrast in the western Pacific warm pool. Then a straightforward question is to what extent or range does this, if any, exist? To answer it, the simultaneous correlation coefficient on each grid has been calculated in the same way as used in the aforementioned regions for the 30–60-day TBB anomaly components between the WARM and COLD cases, and is given in Fig. 4. The dark shading denotes areas with positive coefficient and the light shading represents negative regions, and the shading labels the areas that exceed the 95% significance level. The figure clearly shows that there is an out-of-phase relationship for the TBB 30–60-day anomaly between the WARM and COLD cases over most of the domain concerned. The regions with negative coefficient exceeding the 95% significance level are mainly concentrated in the tropical/extratropical western Pacific, the Indo-China Peninsula, the South China Sea, the East Asian monsoon region, and the Indonesia archipelago. This means a notable phase contrast exists in the 30–60-day TBB anomaly between WARM and COLD over these regions. Therefore it is rational to deduce that the phase variations of the TBB anomaly in the 30–60-day band largely depend on the interannual variability of the thermal state in the western Pacific warm pool. This might be a manifestation of the interactions between the convection on interannual and intraseasonal time scales. However this relation of MJO should not be understood valid in all seasons since the data used is only from May to September. Whether there exists such a relationship in other seasons needs to be studied in the future.

4. Space-time evolution of convection and lower circulation anomalies in the 30–60-day band

To examine the relationships between the convection anomalies and lower circulation anomalies in the 30–60-day band in the WARM and COLD cases, we divide the complete cycle of filtered TBB anomalies into six stages as shown in Fig. 5 based on the normalized time series of 30–60-day TBB anomalies over the western Pacific warm pool in the upper panel of Fig. 3. A total of five cycles in the WARM and COLD cases are considered by composite technique and the results are shown in Fig. 6 and Fig. 7, respectively. The TBB negative (positive) anomalies less (greater) than −1°C are darkly (lightly) shaded in both Fig. 6 and Fig. 7. For brevity we will omit the phrase "30–60-day" in the following discussion although in fact we do concern the features of 30–60-day oscillations. In the WARM case (Fig. 6), at stage 1 (upper panel), when the convection anomaly over the western Pacific warm pool is weak (positive TBB anomaly), suppressed convection is seen over the Bay of Bengal, the South China Sea, and the tropical western Pacific east of the Philippines accompanied with an anomalous anticyclonic circulation at 850 hPa covering the Asia-Western Pacific regions. Northwest of this anticyclone, enhanced convection can be found over North China. Another anomalous anticyclone is developing over the northern Pacific with enhanced convection anomalies overlying its western/northwestern portion. Furthermore, an anomalous cyclonic circulation occupies the equatorial eastern Indian Ocean with enhanced convection showing up to its south. From stage 2 (middle panel) to stage 3 (lower panel), with the convection over the western Pacific warm pool gradually strengthening to a peak (stage 3), the anomalous anticyclonic circulation at 850 hPa which previously controlled the Asia-Western

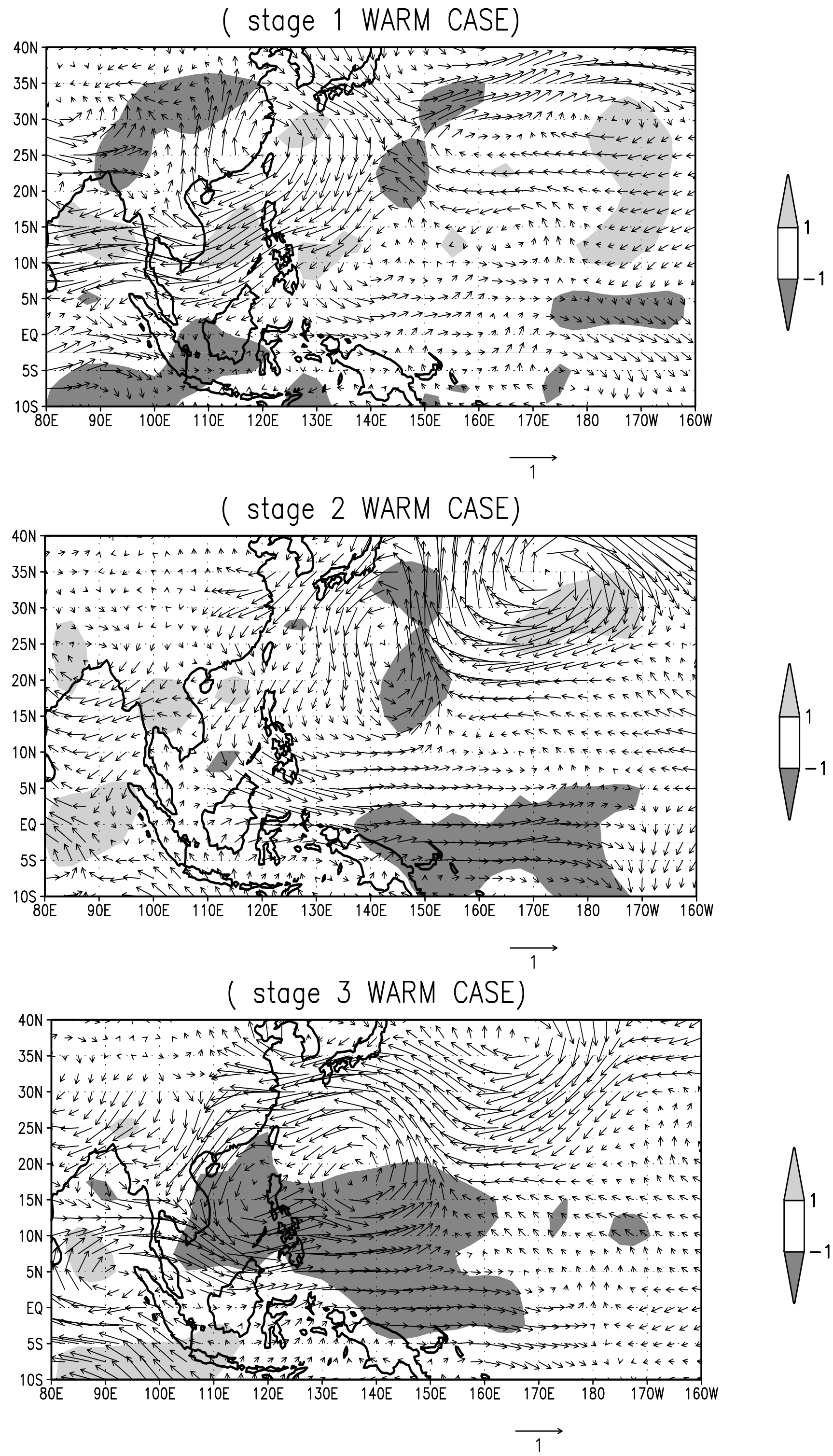

Fig. 6. Spatial distribution of composite TBB and 850 hPa vector wind anomalies in the 30–60-day range from stage 1 through stage 6 in the WARM case. TBB anomalies less (greater) than –1 (1) K are darkly (lightly) shaded.

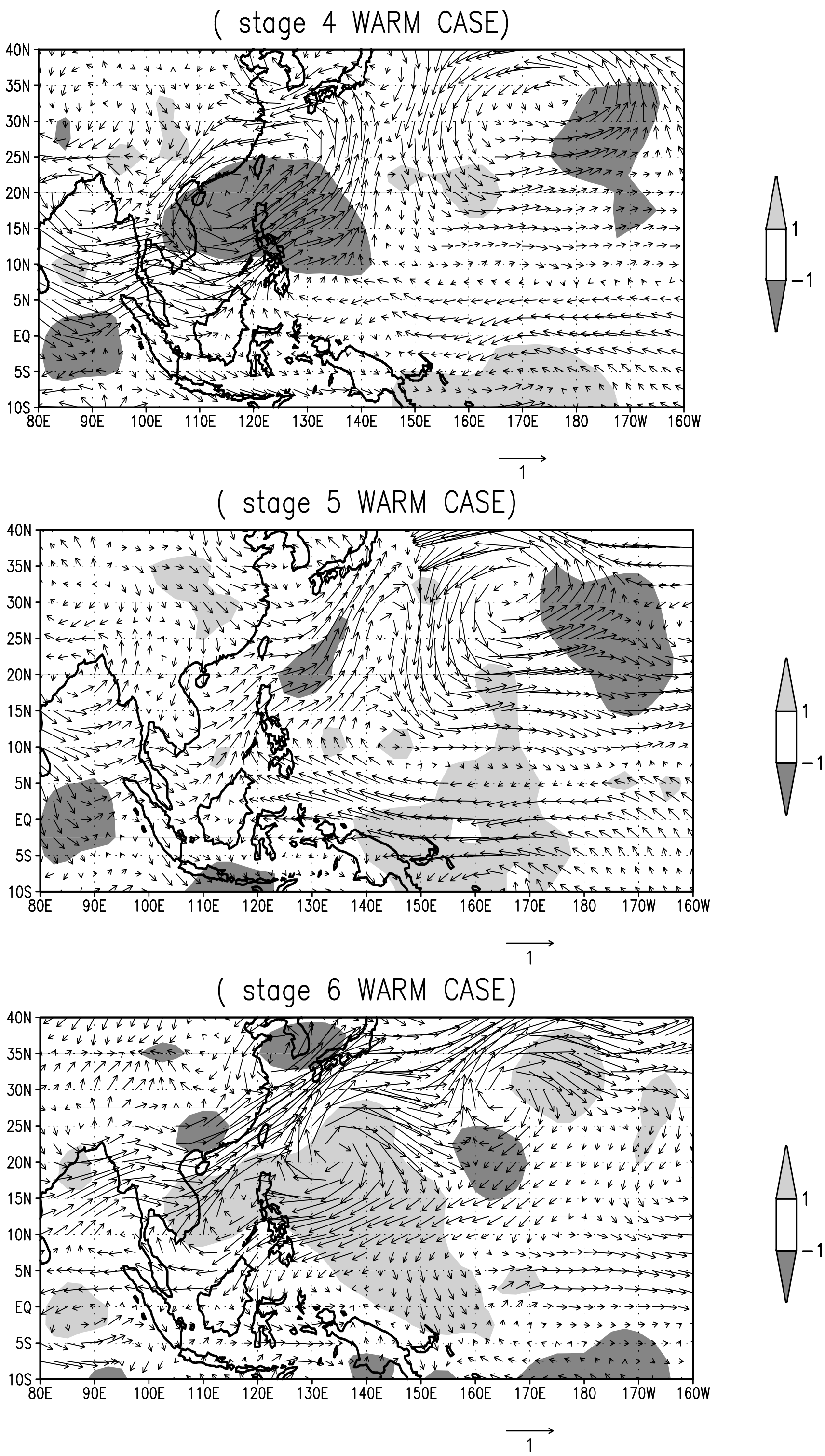

Fig. 6. (Continued)

Pacific regions has vanished and been replaced with a weak but developing anomalous cyclonic circulation at stage 2. This anomalous cyclonic circulation becomes strongest at stage 3, consistent with the most enhanced convection over the western Pacific warm pool and over the South China Sea. Accordingly westerly anomalies appear over the western Pacific warm pool east to the Philippines. Noteworthy is the anticyclone over the northern Pacific which is also intensified and tilted to the west of its original position at stage 1 and it merges with and reinforces the anomalous cyclonic circulation at stage 3. It is interesting to see that the convection is firstly enhanced over the equatorial western/central Pacific at stage 2 and then moves westward/northwestward to the western Pacific warm pool and the South China Sea regions, which is associated well with the strongest westerly anomalies south to the anomalous cyclonic circulation. Meanwhile, another anticyclonic circulation is also established over the eastern Indian Ocean north of the equator with a westerly blowing to the east and converging into the anomalous cyclonic circulation. The convection over the western Pacific warm pool, after the peak phase (stage 3), begins to weaken. And it is easy to see that at stage 4, the enhanced convection is now located over an area within 10°–20°N and 100°–140°E, showing an obvious northwestward shift as compared to its position at stage 3. Correspondingly, the strong anomalous cyclone governing the Asian-Western Pacific seems also to have a northwestward movement/development, which is in good agreement with the northwestward shift of the enhanced convection over the western Pacific warm pool. Concurrently, anomalous stronger westerlies/southwesterlies intruding from the Bay of Bengal strengthen this cyclone. The anticyclone formerly persisting over the northern Pacific disappears and is substituted with an anomalous anticyclonic circulation. Along with the advent of stage 5, the Asian-Western Pacific anomalous cyclone seen in stage 4 vanishes and an anticyclonic circulation develops over the above-mentioned domains. Enhanced convection is confined only over a small portion of area to the north of the South China Sea and the Philippines. Meanwhile, the northern Pacific anomalous cyclone intensifies substantially. In fact, starting from stage 4, the anomalous westerly over the western Pacific warm pool is superseded by an anomalous easterly. Stage 6 corresponds to the weakest convection phase over the western Pacific warm pool, and it is seen that the anomalous, strong anticyclone has grown up well over the Asian-Western Pacific regions covering the South China Sea, the tropical western Pacific, and along the East Asian maritime continent. Consistent with this mature anticyclone, reduced convection is anchored over the above-mentioned domains. Enhanced convection emerges over the northwestern tip of this strong anticyclone, namely, over Korea and the southern part of Japan. Moreover, the former northern Pacific strong anomalous cyclone moves out of sight and turns to the intense westerly joining into the Asian-Western Pacific anomalous anticyclone. In addition, there is another weak anomalous anticyclonic circulation over the Bay of Bengal with a prevailing westerly/southwesterly stretching poleward into the East Asian monsoon region.

Equal analysis is also devoted to the COLD case as shown in Fig. 7. On the one hand, the evolutions of the 30–60-day convections and circulations in both cases are characterized by much in common. They are both dominated by the alternation of anomalous cyclone/anticyclone gradually developing over East Asia and the tropical western Pacific with the mature anomalous cyclone (anticyclone) corresponding to the strongest (weakest) anomalous convection over the western Pacific warm pool. On the other hand, they do show distinct features during different evolution stages. For example, at stage 1, shown in the figure is a unified zonal-oriented anticyclone over East Asia, the tropical western Pacific, and the northern Pacific in the COLD case (Fig. 7), while in the WARM case (Fig. 6), two prominent anticyclones are visible over the above regions. At stage 2, a westerly prevails over the Bay of Bengal in the COLD case but an easterly is seen instead in the WARM, etc. In general, the northern Pacific anomalous cyclone/anticyclone could be distinguished from the anomalous cyclone or anticyclone over East Asia and the tropical western Pacific during the evolving stages in the WARM case, which is often blurred and is not discernable in the COLD case. Besides, it is interesting to note that at stage 6 (minimal convection over the western pacific warm pool), an anomalous westerly/southwesterly prevails over the Bay of Bengal and acts as the principal source of the southwesterly blowing to the East Asian monsoon region in the WARM case, yet in the COLD case, the anomalous easterly dominates over the Bay of Bengal and the southwesterly flowing to the East Asian monsoon region is mainly from the turning of the easterly over the tropical western Pacific. There also appear diversities in convection development between the WARM and COLD cases. For instance, in the WARM case, during the convection over the western Pacific warm pool strengthening from stage 2 to stage 3 (weakening from stage 5 to stage 6), enhanced convection (suppressed convection) seems to go from the equatorial western/central Pacific northwestward

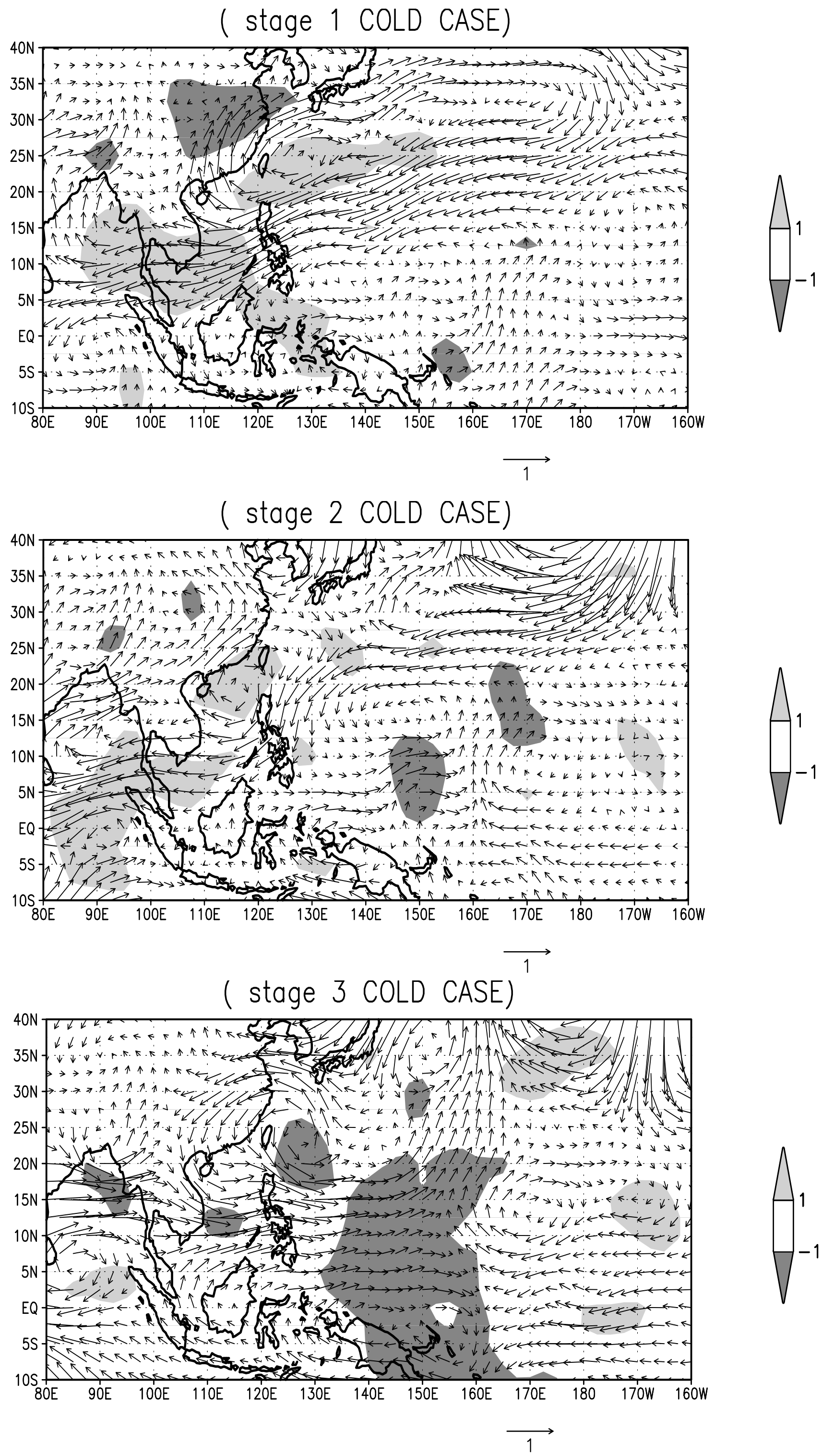

Fig. 7. Spatial distribution of composite TBB and 850 hPa vector wind anomalies in the 30–60-day range from stage 1 through stage 6 in the COLD case. TBB anomalies less (greater) than –1 (1) K are darkly (lightly) shaded.

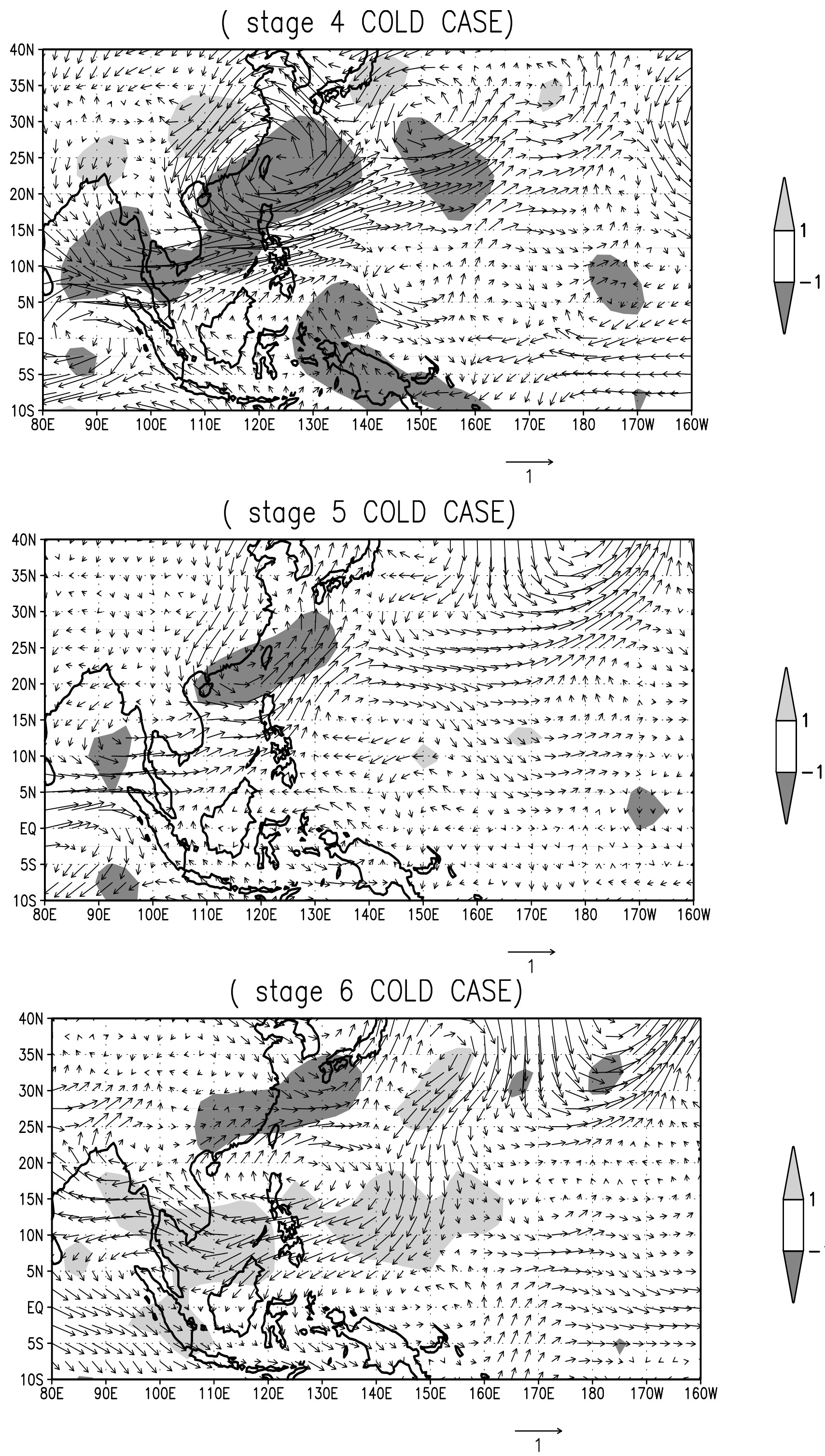

Fig. 7. (Continued)

to the western Pacific warm pool, while in the COLD case, the convection shows "quasi-stationarity"

Both the WARM and COLD cases possess consistent convection and circulation relations on the 30–60-day time scale which is in good agreement with Gill (1980), e.g., an anomalous cyclone (anticyclone) dominates over East Asia and the tropical western Pacific when the convection over the western Pacific warm pool is enhancing (reducing) and concurrently the convection over East Asia is reducing (enhancing). These might reflect the inherent nature between the anomalous convection and the circulation on this time scale. On the other hand, the above analysis discloses diverse evolution characteristics between the WARM and COLD cases, indicating possible influences due to the interannual thermal contrast over the western Pacific warm pool or the possible coherent mutual interactions between variations on the intraseasonal and on the interannual time scales.

5. Summary and discussion

In this paper, we investigate some features of convection and lower circulation anomalies in the 30–60-day range during boreal summer. Particulars are focused on the impact of the thermal state in the western Pacific warm pool on the variation of 30–60-day intraseasonal oscillation. We initiate our work with two cases (WARM and COLD) in accord with the extreme warm and cold summers in the western Pacific warm pool, the same as defined in Ren and Huang (2002). We obtain the filtered 30–60-day time series from May to September for the WARM and COLD cases by composite of the five warm (cold) summers' filtered 30–60-day component.

The composite variance anomalies of TBB in the 30–60-day time band exhibit positive (negative) polarity over the tropical western Pacific in the WARM (COLD) case, implying intensified (reduced) 30–60-day oscillation amplitude of the convection in association with the thermal state of the western Pacific warm pool. The significant anticorrelations of 30–60-day convection oscillations between the WARM and COLD cases over most of the Asian-Pacific regions also demonstrate that the phase variations of 30–60-day convection oscillation can be modulated by the thermal contrast over the western Pacific warm pool, manifesting the interactions between 30–60-day intraseasonal oscillation and the interannual variability of convections. These multi-scale interactions are further felt through the evolution disparities in the 30–60-day components of convection and circulation between the WARM and COLD composite cases. On the other hand, either in the WARM or in the COLD case, a well-organized anomalous cyclone (anticyclone) over the Asian-Western Pacific region in conjunction with the peak enhanced (suppressed) convection over the western Pacific warm pool may be evidence that this type of convection-circulation relation is an essence of 30–60-day intraseasonal oscillations. Besides this convection-circulation relation is in good agreement with that proposed by Gill (1980) in that the low-level cyclonic circulation is located to the northwestward of the enhanced convection region.

Many studies have argued that the Madden-Julian Oscillation (MJO) or 30–60-day oscillation may be a coupled atmosphere-ocean phenomena (e.g., Flatau et al., 1997; Hendon and Glick, 1997; Woolnough et al., 2000). On the one hand, the sea surface temperature in the warm pool is modulated by the passages of MJO and the surface flux associated with it (e.g., Weller and Anderson, 1996; Lau and Sui, 1997). On the other hand, some GCM model studies have also showed that the tropical convection of MJO could be organized by intraseasonal varying SSTs to be relevant to the observations (e.g., Woolnough et al., 2001). Our results also support the hypothesis that MJO is a coupled atmosphere-ocean appearance. In addition, it shows that there may exist interactions between MJO and interannual variability of sea surface temperature in the western Pacific warm pool. Since the interannual variability of SST in the western Pacific warm pool is crucial to Asian climate, it deserves future investigation of what process is responsible for these interactions.

Acknowledgments. Thanks to Dr. Xueshun Shen for kindly providing the TBB data used in the study. The first author would like to appreciate Dr. Riyu Lu for many comments and suggestions. This work was supported by the National Natural Science Foundation of China under Grant No. 40275013, the National Key Programme for Developing Basic Sciences (G1998040900-part 1), and LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences.

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