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10–25–Day Intraseasonal Variations of Convection and Circulation Associated with Thermal State of the Western Pacific Warm Pool during Boreal Summer①

Ren Baohua (任保华)②

Department of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026

Huang Ronghui (黄荣辉)

Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029

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ABSTRACT

This study focuses on the characteristics of 10–25–day oscillation associated with the interannual variability of the thermal state in the western Pacific warm pool. The time series of 10–25–day oscillation shows a distinct feature between warm (WARM case) and cold (COLD case) summers over the western Pacific warm pool. The significant negative relationship between the time series of 10–25–day convection anomalies in Warm and Cold cases appears over most of Asian–Pacific region manifesting the interactions between the convection on interannual and 10–25–day intraseasonal time scales. At the peak and trough stages of 10–25–day convection oscillation, a Gill–type low–level atmospheric circulation anomaly, cyclonic or anticyclonic, appears northwest of the convection anomaly. This relationship between the convection and circulation exists both in Warm case and in Cold case. However, at other stages rather than the peak and trough stages, there is no Gill–type circulation response, and the circulation anomaly shows a distinct feature between the Warm and Cold cases, although the convection oscillation exhibits a roughly similar feature.

Key words: 10–25–day oscillation, Intraseasonal variations, Convection, Circulation, Western pacific warm pool

1. Introduction

After the pioneering work made by Madden and Julian (Madden and Julian 1971, 1972), the intraseasonal oscillation has been the topic by many researchers over decades. Much of those studies centered on the intraseasonal oscillation with time scale 30–60 days (or so–called MJO) which is regarded as a dominant mode of variability in the tropics. The 30–60–day oscillation manifested as large–scale eastward propagating circulation anomalies and associated convection anomalies (e.g., Knutson and Weickmann, 1987; Murakami and Nakazawa 1985) and northward propagating over the Indian monsoon region (Yasunari 1981; Krishnamurti and Subrahmanyam 1982), association with the active / break cycle of the Indian summer monsoon (Murakami et al. 1986; Lau and Chen 1986). Some studies also showed that it interacts with mid–latitude (Lau and Phillips 1986) and bears relationship with ENSO (Lau and Shen 1988; Vincent et al. 1998; Li and Li 1998) and the South China Sea

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② E–mail: ren@ustc.edu.cn

summer monsoon (Mu and Li 2000). Furthermore, the 30–60–day oscillation is phase–locked (Nakazawa 1992; Wang and Xu 1997).

On the other hand, the intraseasonal variation in 10–25 (6–25)–day period is also important for the climate variability. This band contains several physical phenomena such as super cloud clusters, monsoon depressions, tropical cyclones, Rossby wave trains, dipoles of convective activity in the zonal and meridional planes and subtropical jet streaks (Vincent et al. 1998). Some studies have noticed 10–20–day intraseasonal oscillations in the Indian monsoon region (Murakami 1976; Yasunari 1979; Chen and Chen 1993). Lau et al. (1988) found a 20–day oscillation in precipitation during the Meiyu regime. Lau and Yang (1996) also found, in the Indo–China Pen. and East Asian region, a clear 15–20 days intraseasonal oscillation of rainfall. Recently, Fukutomi and Yasunari (1999) examined 10–25–day intraseasonal variations of convection and circulation over East Asia and the western North Pacific in summer and emphasized the associations between the convection over the South China Sea and the circulation over the East Asian monsoon region on 10–25 days time scale. Besides, Vincent et al. (1998) also studied the 6–25–day intraseasonal variation of OLR related to ENSO time scale.

As is well known, the western Pacific warm pool is a key region to 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). Then, a question may arise how the 10–25–day intraseasonal oscillation is associated with the interannual variability of thermal state in the western Pacific warm pool. In this paper, we will investigate the characteristics of convection and lower tropospheric circulation on this time scale associated with extreme warm (cold) thermal state in the western Pacific warm pool during summer. The organization of the paper is as follows. Section 2 is the description of data and method. The interannual variability of the western Pacific warm pool is described in section 3. The composite features of convection anomalies on 10–25–day band are shown in section 4. Section 5 is the result for 10–25–day oscillation space–time evolution of convection and lower circulation anomalies. Summary and discussion are presented in section 6.

2. Data and method

Satellite–observed Equivalent Temperature of Black Body at Cloud Top (TBB) dataset from Japan Meteorology Agency is used as a proxy for convection in the study. The TBB records are grid data with resolution 1° × 1°, 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 those hourly data each day. The NCEP / NCAR reanalysis daily 2.5° × 2.5° grid wind dataset at 850 hPa for the same period as TBB is also utilized.

In this study, we use 18–year summer's daily data from May to September. For those daily data (TBB and wind at 850 hPa), we firstly calculated their daily anomalies by subtracting them from their corresponding climatological daily mean. Then their seasonal trends were also removed by subtracting the quadratic trend at each grid point. Secondly we applied a band–pass filter as in Murakami (1979) to those detrended daily anomalies to retain their 10–25–day components for each summer.

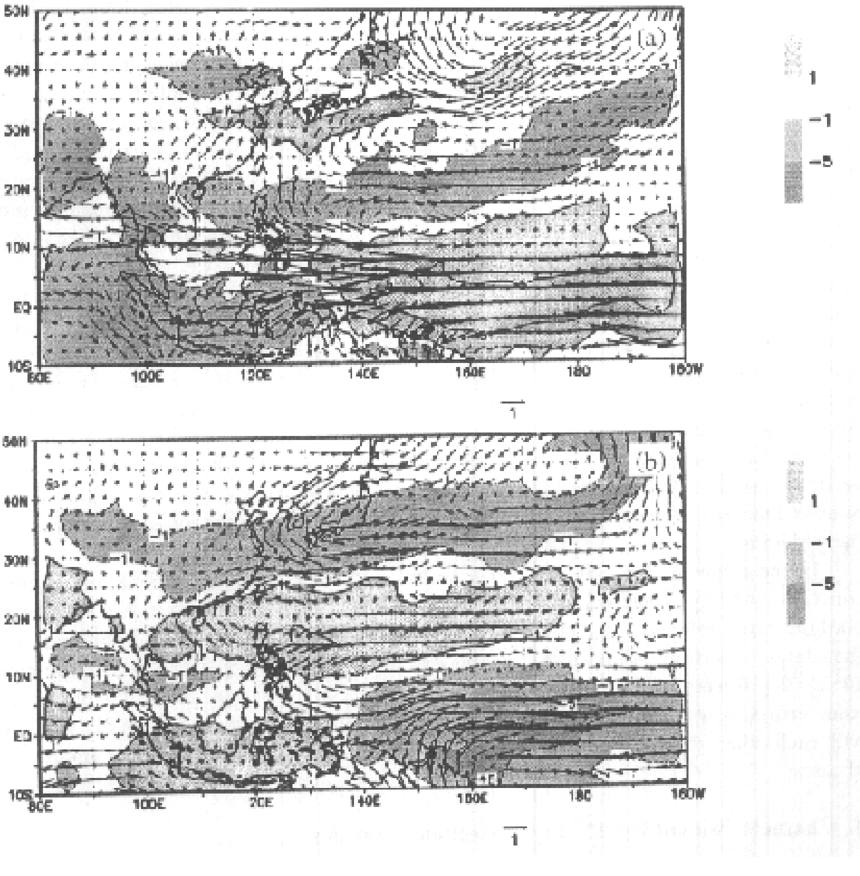


Fig. 1. Composite distribution of JJA–averaged TBB and wind anomalies at 850 hPa for warm (a) and cold (b) summers in the western Pacific warm pool. Dark (light) shaded areas denote negative (positive) TBB anomalies corresponding to enhanced (suppressed) convection less (greater) than −1(1) K with darkest areas less than −5 K.

3. Distributions of anomalous convection and lower circulation associated with extreme warm (cold) summers of the western pacific warm pool

In this section, we will show composite results associated with warm (cold) states in the western Pacific warm pool. The western Pacific warm pool is confined within 0°–14°N, 130°–150°E, consistent with Huang and Sun (1992). The procedure is as follows: The time series of June–July–August averaged anomaly of SSTs in the western Pacific warm pool region were firstly obtained from monthly SSTs (figure omitted). Those years with JJA anomaly of SSTs greater than (less than) one standard deviation of anomalies were defined as warm (cold) ones when the western Pacific warm pool are in the extreme warm (cold) summers. By these criteria, five warm (cold) summers were picked out, i.e. 1981, 1984, 1988, 1995, 1996 (1980, 1982, 1983, 1993, 1997), respectively. The composite technique was then applied to the JJA anomalous convection and lower circulation for warm (cold) summers and shown in Fig. 1. The shaded area in Fig. 1 represent stronger convection than normal (TBB anomaly less than −1 K). In the warm case (upper panel), a well−organized enhanced convection zone starting from over the South China Sea and the Philippines elongates eastward and / or northeastward covering the tropical western and northwestern Pacific with underlying anomalous westerly emerging from an anomalous cyclone to its north and an anomalous anticyclone to its south. In the equatorial Indian Ocean, stronger convection than normal could also be noticed accompanied with an anomalous cyclonic flow in the lower troposphere. A weak anticyclonic flow at 850 hPa occupying the East Asian monsoon region corresponds to the suppressed convection overlying. The convection in the equatorial central Pacific is found weaker than normal coupled with prevailing anomalous easterlies at 850 hPa. In the cold composite (lower panel), the situation is almost reverse to the warm composite. The enhanced convection appears over the East Asian monsoon region and the equatorial central Pacific. Accordingly at 850 hPa, anomalous cyclonic flows prevail in the East Asian monsoon region and significant westerly stretches along the equatorial central Pacific. As is expected, the convection over the equatorial Indian Ocean, the tropical western Pacific warm pool and the South China Sea is weak with underlying anomalous easterly in the lower troposphere over these regions.

In the following sections, we will examine the 10−25−day intraseasonal oscillation of convection and lower circulation for the warm and cold summers of the western Pacific warm pool (hereafter referred to as WARM (COLD) case). The analysis is based upon the composite dataset that is obtained by averaging the corresponding warm (cold) summers' 10−25−day filtered TBB and wind data. Though this composite technique might introduce some errors in which some positive and negative values in composite probably counteract with each other, the composite result can still retain the general features for an uniform kind of cases.

4. Characteristics of 10−25−day convection anomalies

4.1 *Spatial distribution of 10−25−day TBB variability*

To detect the dominant locations of the 10−25−day oscillation of convection, we will show the spatial distribution of the convection variance on this time band from May to September. The variance is defined as

$$\sigma^2_{(\mathrm{case})} = \sum_{n=1}^{n=153} \frac{[\mathrm{TBB}_{(\mathrm{case})}(n)]^2}{153} \quad . \tag{1}$$

The subscript " case" is added to (1) to indicate that the 10−25−day bandpass−filtered TBB data in warm and cold cases enter the formula. The variance of the detrended TBB daily data is also estimated with Formula (1) by simply using the detrended TBB daily data in the numerator. Then we could easily find the ratio of the variance of 10−25−day TBB data to that of the detrended TBB daily data.

Figure 2 and Fig. 3 show the spatial distribution of the 10−25−day TBB variance and its

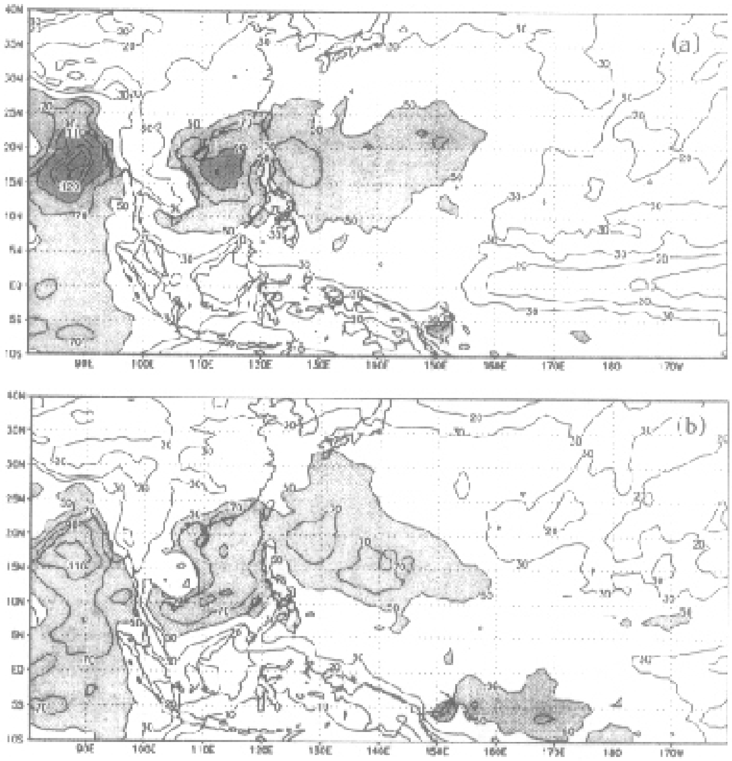


Fig. 2. The variance of TBB anomaly on 10–25–day band from May to September for (a) WARM case and (b) COLD case. The shaded areas denote variance exceeding 50 K^2.

ratio to that of the detrended TBB daily data, respectively. Examination of the figure reveals some inherent features of the 10–25–day oscillation of convection.

The geographical locations of large amplitude of convection on 10–25–day band inhabit over the Indian Ocean and the tropical / extratropical western Pacific off the equator in either WARM or COLD case as evident from Fig. 2a and Fig. 2b. Vincent et al. (1998) also noticed this phenomenon by using 20–year OLR data.

The ratio distribution also display that the regions of ratio exceeding 0.2 (20%) are mainly located in the tropics / extratropics off the equator including the Bay of Bengal, the South China Sea and the western and / or northwestern Pacific. The location of larger ratio and larger variance of 10–25–day band (variance greater than 50 K^2) are not correspondent each other entirely.

The results indicate that the 10–25–day oscillation of convection, in a sense of its variance, is universal and "location–locking" and has little interannual variability.

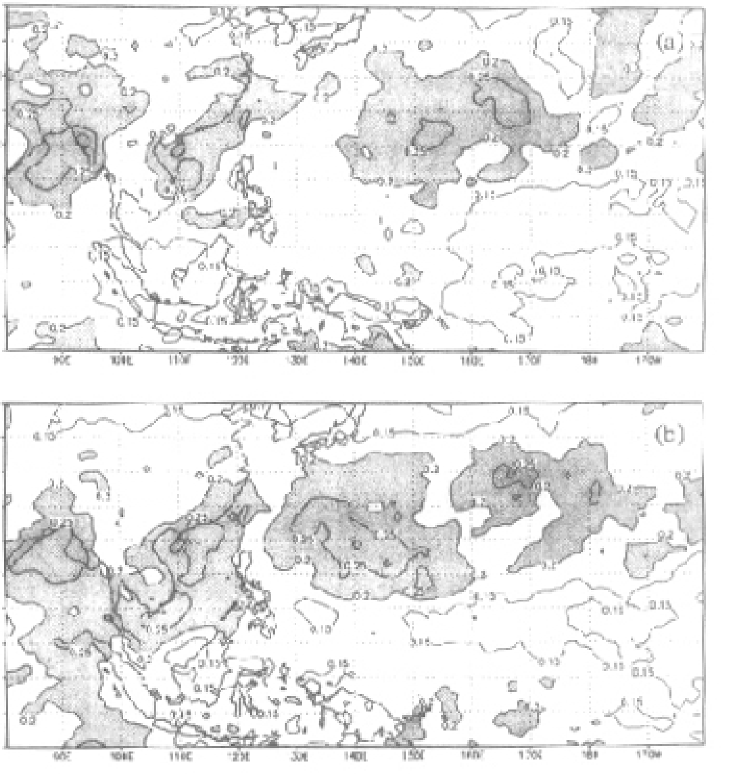


Fig. 3. The percentage of the variance of TBB anomaly on 10–25–day band to that unfilered TBB daily data from May to September for (a) WARM case and (b) COLD case. The shaded areas denote the percentage exceeding 0.2 (20%).

4.2 *Temporal variability of the convection on 10–25–day band*

To examine the phase variation of 10–25–day oscillation of the convection, Fig. 4 shows the realizations of 10–25–day TBB anomaly over three preferred regions, the tropical western Pacific (a), the South China Sea (b) and the East Asian monsoon region represented by the Yangtze River and Huaihe River (c) in WARM and COLD cases, respectively. The curves have been normalized by their corresponding standard deviations before display. Also shown in the figure is the simultaneous correlation coefficient between the time series in WARM case and that in COLD case from May 1st to September 30th 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. Thus the convection over the three regions discloses a dominant negative relationship between the WARM and COLD cases on 10–25–day band, which implies that this peculiar out–of–phase relationship between WARM and COLD cases is

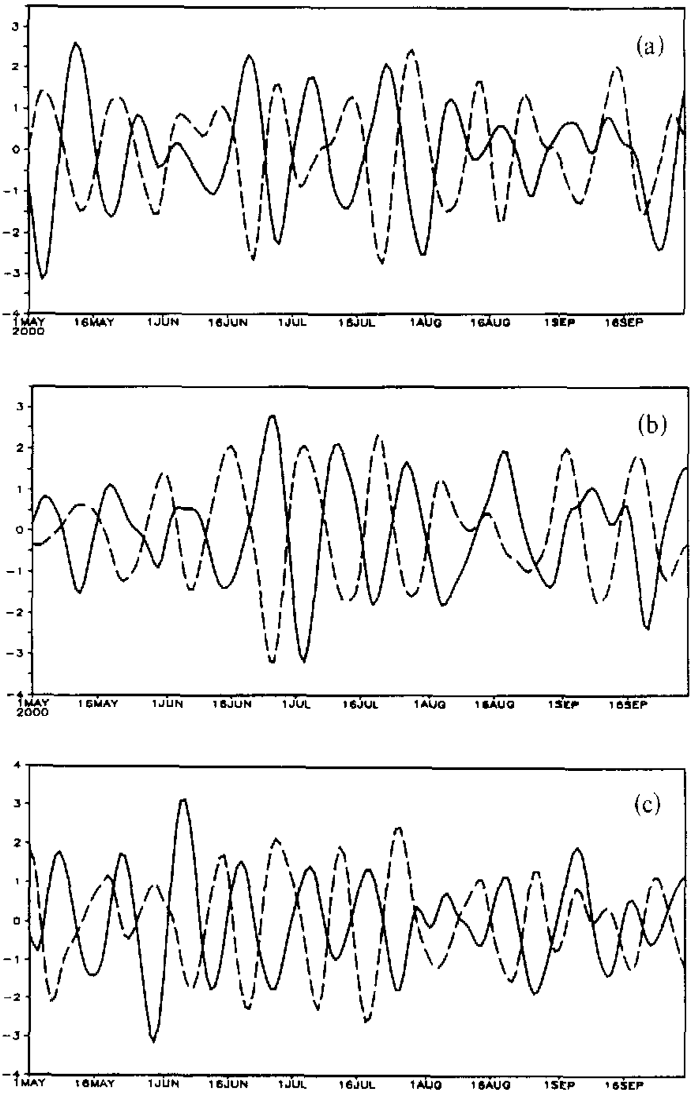


Fig. 4. Normalized time series of TBB 10–25-day anomaly in WARM (solid) and COLD (dashed) cases over (a) the tropical western Pacific, (b) the South China Sea and (c) the Yangtze River and Huaihe River.

probably attributed to the interannual thermal contrast in the western Pacific warm pool. Then a straightforward question will be, to what extent or range does this bearing, if any, exist? To answer it, simultaneous correlation coefficient on each grid has been calculated in the same way as used in the aforementioned regions for the 10–25–day TBB anomaly between WARM and COLD cases which is listed in Fig. 5. The darkest shaded areas without labeling denote the regions with positive coefficients and the light shaded areas represent negative regions at the significance level exceeding 95%. The figure clearly shows that there exists an

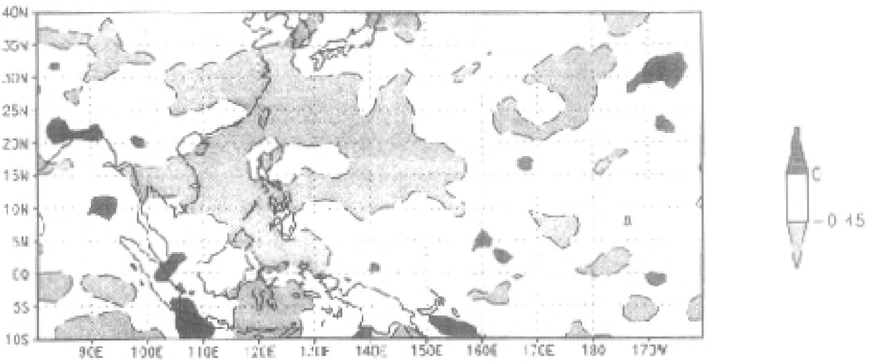


Fig. 5. Simultaneous correlation between WARM and COLD of TBB anomalies on 10–25–day band between WARM and COLD cases from May 1 to September 30. The darkest shaded areas represent positive values. The others negative. Light shaded areas denote the correlation coefficient exceeding 95% significance level.

out–of–phase relationship for TBB 10–25–day anomaly between WARM and COLD cases over most of the domain concerned. The regions with negative coefficients exceeding 95% significance level 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, which means a notable phase contrast existing in 10–25–day TBB anomaly between WARM and COLD cases over these regions. Thus it is rational to deduce that the phase variations of TBB anomaly on 10–25–day band depend largely on the interannual variability of the thermal state in the western Pacific warm pool, which might be a manifestation of the interactions between the convection on interannual and intraseasonal time scales. Also interesting is the emerging of some positive coefficient areas though scattering and taking up only a very small portion of the whole domain. The positive correlation in the Bay of Bengal is worthy of attention since the variance of 10–25–day TBB anomaly or its ratio to the unfiltered daily TBB anomaly is larger in either WARM or COLD cases as shown in Fig. 2 and Fig. 3. The positive correlation could be explained as that the phase of 10–25–day TBB anomaly over the Bay of Bengal is less or not influenced by the interannual variability of the thermal state in the western Pacific warm pool, which further implies that the 10–25–day convection over the Bay of Bengal might belong to a different system independent of that over the western Pacific.

5. Space–time evolution of convection and lower circulation anomalies on 10–25–day band

In this section, we will examine the relationship between the convection anomalies and lower circulation anomalies on 10–25–day band in WARM and COLD cases, respectively. For this reason, we have divided the complete cycle of filtered TBB anomalies into six stages as shown in Fig. 6b based on Fig. 6a. The ' P' in Fig. 6a represents stage 3 (peak phase). A total of five cycles in WARM (COLD) case were considered by the composite technique and the results shown in Fig. 7 and Fig. 8, respectively. The TBB negative (positive) anomalies less (greater) than –1 (1)°C are darkly (lightly) shaded in both Fig. 7 and Fig. 8. Let's first focus

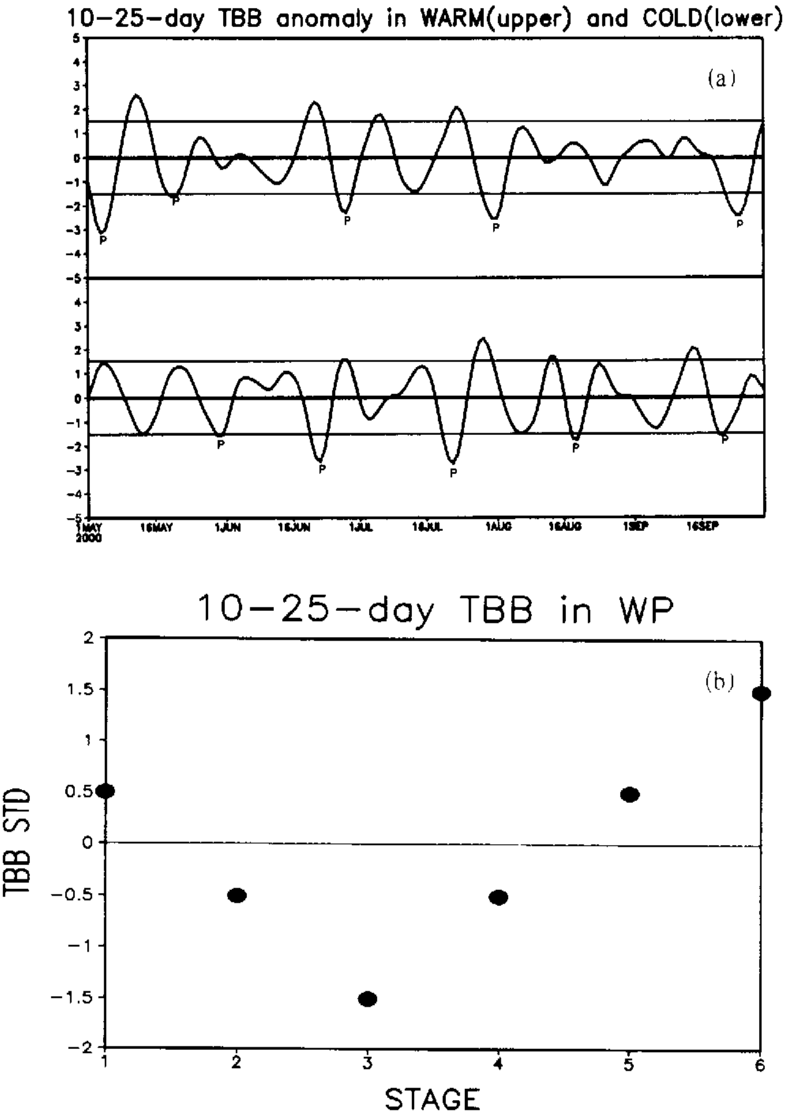
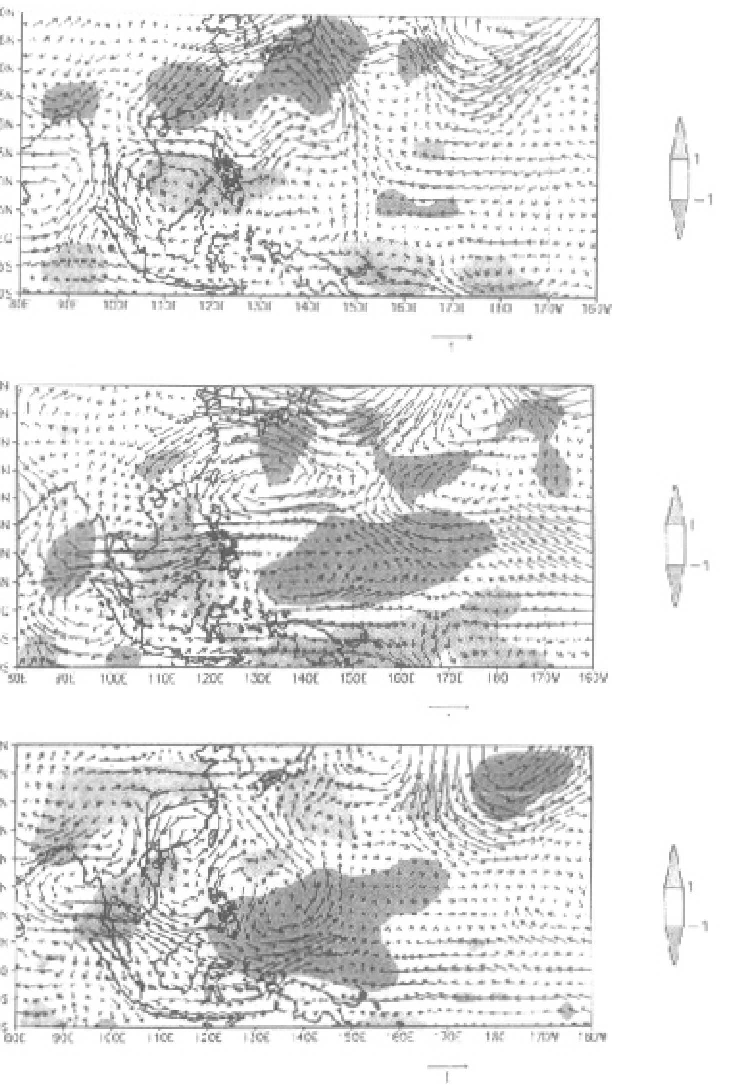


Fig. 6. (a) Normalized time series in the western Pacific warm pool. The label " P" stands for peak value and will be used in the composite. (b) Sketch map showing the stages for composite, black dots indicate the stages from stage 1 to stage 6.

on the evolution in WARM case as shown in Fig. 7. At stage 1, enhanced convection anomalies appear over the East Asian monsoon region including the eastern part of China and Japan in conjunction with anomalous cyclonic circulation at lower level. A weak anticyclonic disturbance covers the Indo–China Peninsula and the Philippines in association with suppressed convection. Also seen is an anomalous anticyclonic circulation over the northwestern Pacific. From stage 1 to stage 3, the anomalous cyclonic circulation originally over the subtropics moves southwestward and at stage 3, its center is located in the tropical western Pacific. Convection gradually weakened over the East Asian monsoon region and intensified to its peak over the tropical western Pacific. Westerly blows from the Bay of Bengal to the tropical western Pacific. Concurrently, convection over the northwestern Pacific is strengthening accompanied with underlying anticyclonic circulation at stage 1 to strong cyclonic circulation at stage 3. Stage 4 is the stage just after the peak-enhanced convection over the



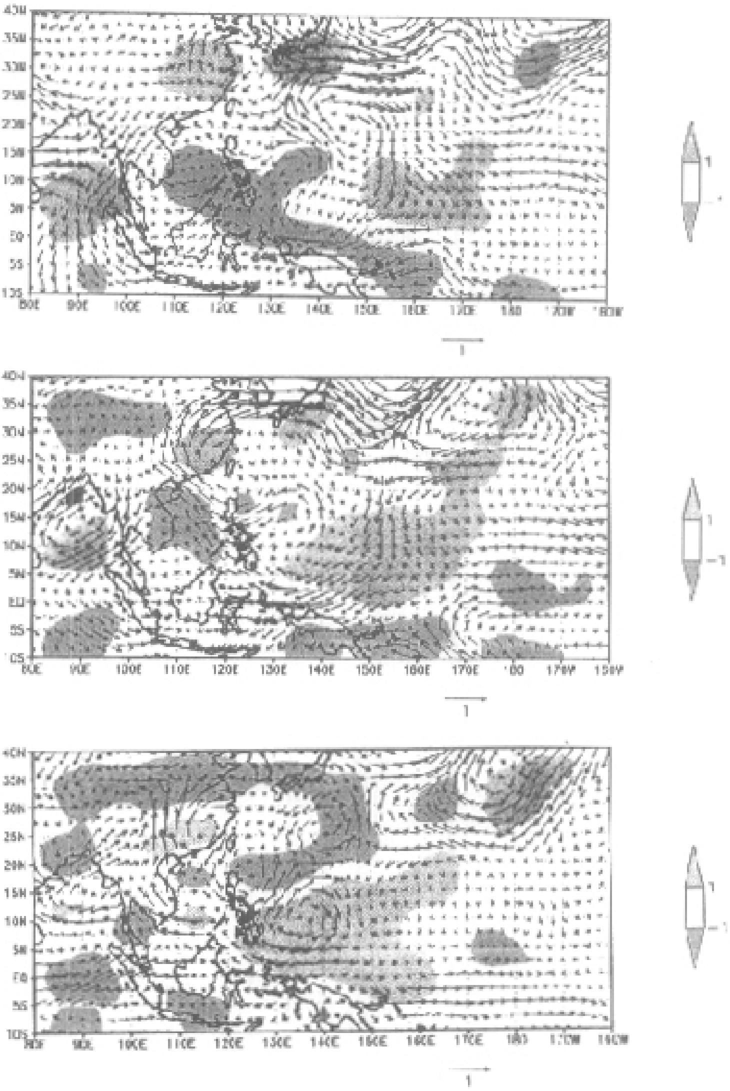
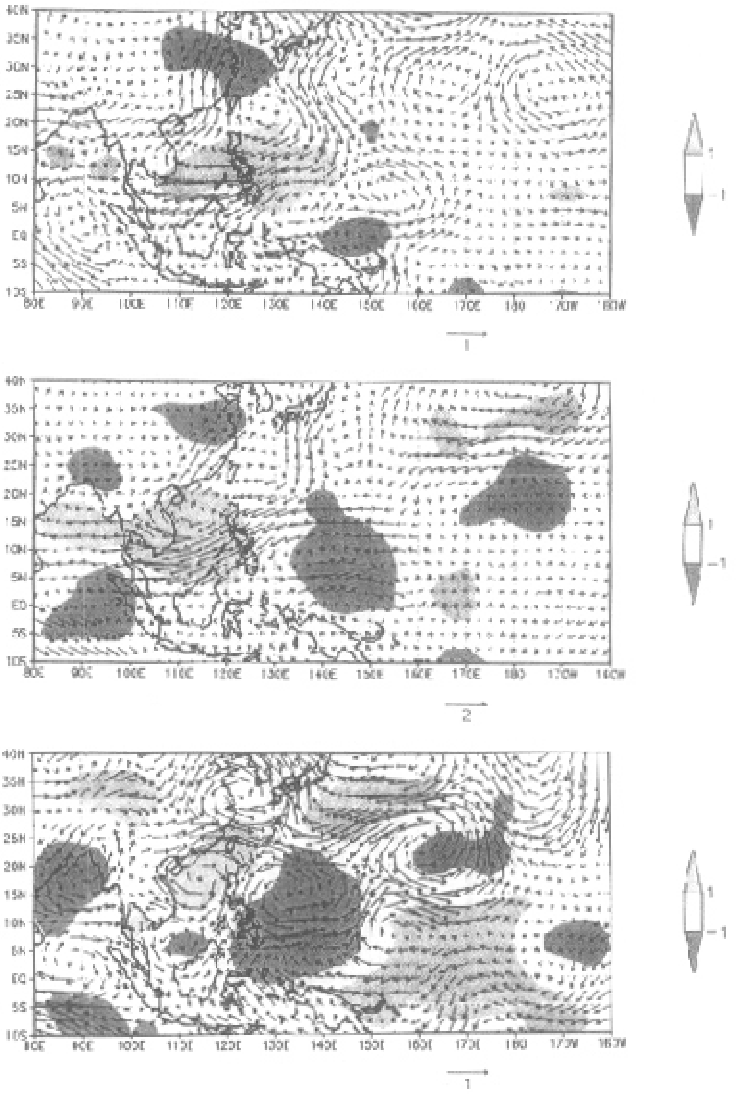


Fig. 7. Spatial distribution of composite TBB and 850 hPa vector wind anomalies in the 10–25–day range from stage 1 through stage 6 in WARM case. TBB anomalies less (greater) than −1(1) K are darkly (lightly) shaded.

tropical western Pacific. Negative TBB anomalies and associated anomalous cyclonic circulation move northwestward from the tropical western Pacific to the South China Sea. An anomalous anticyclonic circulation is developing over the western warm pool and the East Asian monsoon region. Convection over the East Asian monsoon region begins to strengthen. You may find from Detailed investigation can find that the stage 4 to stage 6 are almost (exactly) the mirror of stage 1 to stage 3, respectively indicating the completion of a full cycle. For instance, at stage 6, the pattern of convection and circulation anomalies is reversed as compared to that at stage 3. Suppressed convection and an anomalous anticyclonic circulation distribute over the tropical western Pacific. While enhanced convection can be seen over



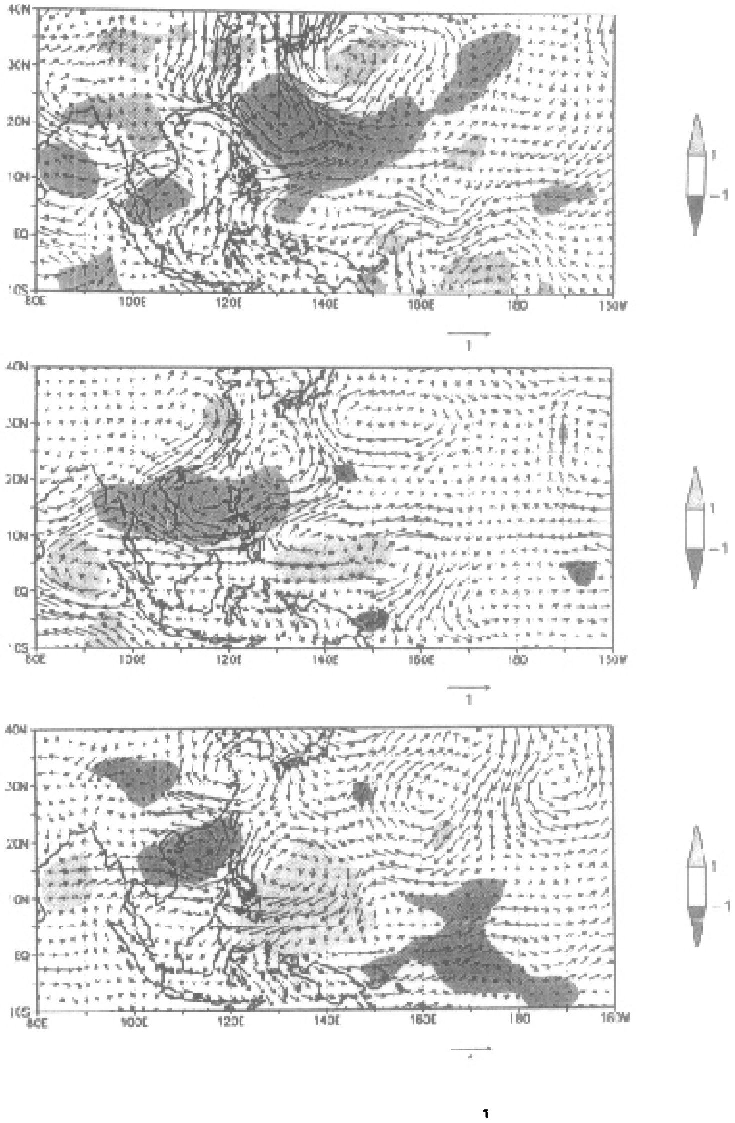


Fig. 8. Same as Fig. 7 but for COLD case.

the subtropics. Accordingly, suppressed convection and anomalous anticyclonic circulation appear over the northwestern Pacific.

Equal analysis has also been devoted to that in COLD case as shown in Fig.8. In order to save space, we will summarize the similarities and differences in the evolution of convection and circulation anomalies on 10–25–day band between WARM and COLD cases. For sake of description, we will call stage 1 and stage 2 developing periods since they correspond to the period of strengthening of convection anomalies over the tropical western Pacific (hereafter referred to as DPP), and call stage 4 and stage 5 decaying period (DCP). Regardless of WARM or COLD case, enhanced (suppressed) convection anomalies are coupled with lower cyclonic (anticyclonic) circulation anomalies over the tropical western Pacific. When convection anomalies over the tropical western Pacific come to its peak enhanced (suppressed) stage of stage 3 (stage 6), suppressed (enhanced) convection anomalies associated with lower cyclonic (anticyclonic) circulation anomalies appear over the EAM region, which implies an out-of-phase relationship between the convection anomalies over the tropical western Pacific and that over the EAM region. Worth of notice is the lower circulation anomalies show a clear Gill-type (Gill 1980) distribution in which anomalous cyclonic (anticyclonic) circulation appears northwest of the convection anomalies at peak stage 3 (stage 6). However, differences are apparent for the evolution of convection and lower circulation anomalies in WARM and COLD cases. During DPP, the evolution manifests a southwestward shift of an anomalous cyclonic (anticyclonic) circulation over the EAM region and the South China Sea with westerly (easterly) anomalies blowing from the Bay of Bengal (the Philippines) to the Philippines (the Bay of Bengal) in WARM (COLD) case. During DCP, the pattern was reversed as compared to that during DPP.

6. Summary and discussion

We investigated some features of convection and lower circulation anomalies in the 10–25–day range during the boreal summer. Particulars are focused on the impact of the thermal state in the western Pacific warm pool on the variation of 10–25–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 defined as the JJA-averaged SSTs' anomalies within the region 130°–150°E, 0°–14°N. Five WARM (COLD) summers are thus selected as the summers of 1981, 1984, 1988, 1995, 1996 (1980, 1982, 1983, 1993, 1997). Then we have filtered 10–25–day time series from May to September for WARM and COLD cases by composite of the five warm (cold) summers' filtered 10–25–day component.

The distribution of the variance of TBB anomalies on 10–25–day band displays a "location-locked" feature in which the larger amplitude of convection anomalies emerge over the eastern Indian Ocean and the tropical / extratropical western Pacific off the equator either in WARM or in COLD case as evident from Fig. 2, which might hint that frequent occurrence of convection anomalies on this intraseasonal time scale over these regions is an inherent nature of the 10–25–day oscillation. In other words, the interannual variability of the thermal state in the western Pacifc warm pool has less or no influence on the activities of convection anomalies on 10–25–day band in a sense of its variance. On the other hand, the phase relationship of convection anomalies on this time scale has shown remarkable out-of-phase correlation between WARM and COLD cases over the Asia-Pacific region indicating the impact of the interannual variability of the thermal state in the western Pacific warm pool on intraseasonal variation of the convection anomalies in 10–25–day range.

The space-time evolutions of convection and circulation anomalies at 850 hPa on 10–25–day time scale disclose that the enhanced (suppressed) convection anomalies are coupled with lower cyclonic (anticyclonic) circulation anomalies over the tropical western Pacific either in WARM or in COLD case. An out-of-phase relationship is also seen between the convection anomalies over the tropical western Pacific and that over the EAM region at peak enhanced (suppressed) stage of stage 3 (stage 6) with suppressed (enhanced) convection anomalies over the EAM region corresponding to enhanced (suppressed) convection anomalies over the tropical western Pacific whether in WARM or in COLD case. Meanwhile the lower anomalous cyclonic (anticyclonic) circulation appearing northwest of the convection anomalies conforms to Gill's theory (Gill 1980). Nevertheless there are some different features related to the evolution of the 10–25–day oscillations. During DPP, the evolution manifests a southwestward shift of an anomalous cyclonic (anticyclonic) circulation over the EAM region and the South China Sea with westerly (easterly) anomalies blowing from the Bay of Bengal (the Philippines) to the Philippines (the Bay of Bengal) in WARM (COLD) case. The reversed pattern was found during DCP as compared to that during DPP.

The variance of daily convection anomalies explained by 10–25–day oscillation is about 20%–25% over the Asia–Pacific region as shown in Fig. 3. Obviously the behavior of convection anomalies on the 10–25–day oscillation is important to the intraseasonal variation of convection over these regions especially on the EAM region. The influences of the interannual variability of the thermal state in the western warm pool on the 10–25–day oscillation take effect by changing the characteristics of the phase of convection anomalies, which might in turn exert impacts on the activities of the East Asian summer monsoon (e.g. monsoon onset and or active / break). However the dynamic mechanism of the interactions between the interannual variability and intraseasonal variability on 10–25–day time scale is still unknown, which is worth of investigating in the future work.

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夏季对流和环流 10–25 天季内变化与西太平洋暖池热力状况的关系

任保华　　黄荣辉

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摘　要

主要讨论了与西太平洋暖池热力状况年际变化相联系的 10–25 天季内振荡的特征. 在西太平洋暖池处于“暖”夏季和“冷”夏季两种状态时, 10–25 天季内振荡呈现出明显差异, 在所讨论的亚洲—太平洋大部分区域, “暖”夏季时对流活动的 10–25 天季内变化和“冷”夏季时对流活动的 10–25 天季内变化表现出显著的反相关关系, 表明对流活动的年际变化与季内变化的相互作用。当西太平洋暖池上空对流活动的 10–25 天季内振荡处于最强和最弱阶段时, 低层大气表现为 Gill 型环流响应, 即气旋式(反气旋式)环流出现在最强(最弱)对流活动的西北. 这种对流和环流关系在西太平洋暖池出于“暖”夏季和“冷”夏季两种状态时均成立。而当西太平洋暖池上空对流活动的 10–25 天季内振荡处于除此以外其他阶段时, 就看不到 Gill 型环流响应.

关键词: 10–25 天振荡, 季内变化, 对流, 环流, 西太平洋暖池