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THE STRONG DRAGON BOAT RACE PRECIPITATION OF GUANGDONG IN 2008 AND QUASI-10-DAY OSCILLATION

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Abstract: Guangdong suffered from the most serious precipitation of its corresponding time during the dragon-boat race of 2008 since 1951. The relationship between the strong dragon-boat precipitation in 2008 and atmospheric low-frequency oscillation was analyzed with the methods of wavelet analysis, correlation and Lanczos filter. Results showed that the daily rainfall exhibits a significant 7 to 12-day quasi-periodic oscillation (namely quasi-10-day oscillation) during the precipitation, the daily 500 hPa height over Guangdong exhibits a significant 8 to 13-day quasi-periodic oscillation, and the daily 850 hPa zonal wind averaged over the north of the South China Sea presents a significant quasi-12-day periodic oscillation. The Guangdong rainfall during the annually first rainy season is most closely correlated with monsoon over the north of South China Sea, and less closely with an upper-level trough at 500 hPa affecting Guangdong. Strong monsoon surges induced two heavy rainfall processes in 2008. The monsoon surges joined with a westward-propagating quasi-10-day oscillation that originated from the central Pacific and was enhanced in a strong convective region east of the Philippines and a northward-propagating monsoon that originated from the southern South China Sea was enhanced. With composite analysis of typical phases, the common evolution characteristics of atmospheric circulation of the two heavy rainfall processes were analyzed for different phases. These features can be used as reference for medium prediction of heavy rainfall processes in Guangdong.

Key words: dragon-boat festival precipitation; upper-level trough at 500 hPa; monsoon over the north of South China Sea; low-frequency oscillation

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1 INTRODUCTION

“Dragon Boat Race” (hereafter referred to as “DBR”) precipitation refers to one that occurs from late May to mid-June when dragon boats are racing festively; it is the most frequent and concentrated during Guangdong’ annually first raining period (April through June, referred to as the “raining season” hereafter). Characterized by continuous heavy, unusually heavy or even exceptionally heavy rainfall for a few days, the DBR precipitation is likely to cause floods or sustained rain and little sunshine^[1]. From late May to mid-June 2008, a DBR rain—the most severe of its kind since 1951—took place in Guangdong province^[2]. Due to its long duration and high rain rates, this DBR rain caused severe flooding

destruction in the Pearl River Delta, eastern Guangdong and part of its northern part that were marked by flash floods, collapsed houses, submerged farmland, and destroyed roads, costing the province huge losses economically.

Since the discovery by Madden et al.^[3, 4] in early 1970s, based on an analysis of observations on the Canton Island, of the existence of 40-50-day periodic low-frequency oscillations in the zonal wind and pressure fields of tropical atmosphere, atmospheric low-frequency oscillations (LFOs) have been an important forefront topic of research in the atmospheric science. Viewed as one of the important circulation systems in the atmosphere, the LFOs, via activity and anomalies, have great impacts on weather

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and climate over extensive areas. The LEOs found in precipitation and its main governing systems also draw the attention of meteorologists both at home and abroad^[5-13]. Most of the existing research in China, however, focuses on the relationships between the (heavy) precipitation in the east of China and the atmospheric LFOs^[14-16], especially between the (heavy) precipitation over the basins of Yangtze and Huaihe Rivers and the LFOs^[17-22], while studying little on the relationships between the heavy precipitation in the south of China, especially Guangdong province, and the LFOs^[23-25].

As they persist for a relatively long time with stable characteristics of activity, the LFOs are a potentially useful means for medium-term, extended-duration and short-term climate prediction. According to Ju et al.^[21] on the effect of LFOs of summer monsoon in East Asia on the drought and flood in the middle and lower reaches of Yangtze River, the ways in which the medium- and short-range LFOs of East Asian monsoon propagate are an important indicator for the medium- and long-term forecast of precipitation in these river reaches. In their study on the relationships between flood-causing heavy rainfall in southern China and monsoon surges, Tao et al.^[26] demonstrated that the Madden-Julian Oscillations (MJOs) from the equatorial Indian Ocean intensifies the westerlies in the South China Sea and triggers the onset of monsoon surges in the southern Chinese continent, which interact with colder air coming from the north and result in flood-causing heavy rainfall on stationary fronts. On the basis of it, they put forward a basic idea of making medium- and short-term forecasts of basin-wide heavy rainfall that causes floods in the south of China. In their study on the relationships between precipitation anomalies in the 1997 raining season in the south of China and the atmospheric LFOs, Xin et al.^[24] determined that the precipitation in this raining season is dominated by quasi-biweekly oscillations of 10 to 20 days and the propagation and variation of low-frequency zonal winds are well corresponding to the temporal distribution of precipitation and their research is useful in improving the skill of forecasting precipitation over extended durations.

With the development of the atmospheric science and computer technology, great progress has been made in the medium-term numerical weather prediction (NWP) that could provide forecasts of situations of atmospheric circulation (e.g. 500 hPa geopotential heights and 850 hPa winds) for 4 to 10 days to come, which prove to be useful for general guidance. The medium-term rainfall forecasting could be improved if the characteristics of atmospheric circulation evolution are captured, together with the use of relevant NWP products, for the time leading up to the onset of severe rain. This paper will be, therefore, arranged in the following order. First, the

LFOs will be analyzed of the rain and atmospheric circulation elements in Guangdong's raining season, and the relationships between the variation of the rain and the quasi-periodic variation of these elements. Then, the effect is studied of the horizontal monsoon propagation on the simultaneous DBR. Finally, evolutions are analyzed of the atmospheric circulation field associated with severe rain during the DBR period in order to work for the medium-range forecast of severe rain, especially the DBR, in Guangdong.

2 DATA AND METHODS

The data used in this study include day-to-day surface rain from 86 stations in Guangdong, which is from Climate Center of Guangdong spanning 1 March through 30 July, and daily reanalysis from NCEP/NCAR ($2.5^{\circ} \times 2.5^{\circ}$).

The Mexican hat wavelet transform^[27] is used to study the periodicity of the time series and low-frequency filter is applied using the Lanczos time filter^[28]. Then, with composite analysis, the evolutionary characteristics through all the phases, common to the two different processes of severe precipitation during the DBR period, are studied of the atmospheric circulation, moisture flux vectors and divergence.

In the Lanczos time filter^[28],

$$y_t = \sum_{k=-n}^n w_k x_{t-k} \quad (1)$$

where x_t is the primitive data, t the variable of time, w_k the function of weighting, y_t the time series after filter, and n the length of the time series.

$$w_k = \frac{\sin 2\pi f_c k}{\pi k} \frac{\sin \pi k / n}{\pi k / n} \quad k=-n, \dots, 0, \dots, n. \quad (2)$$

where f_c is the frequency of truncation, i.e., responses fall rapidly from 1 to 0 near the frequency^[28].

Following Zhang et al.^[29], moisture flux (F) and its divergence ($\nabla \cdot F$) are respectively expressed by

$$F = \frac{1}{g} qV \quad (3)$$

$$\nabla \cdot F = \frac{1}{g} \nabla \cdot (qV) = \frac{1}{g} \left[\frac{\partial}{\partial x} (uq) + \frac{\partial}{\partial y} (vq) \right] \quad (4)$$

where V is the horizontal wind and q the specific humidity, the direction of F is the same as that of V and the direction of the horizontal wind is used to indicate that of the moisture flux propagation.

3 LOW-FREQUENCY CHARACTERISTICS OF THE RAIN IN RAINING SEASON OF GUANGDONG AND ELEMENTS OF ATMOSPHERIC CIRCULATION

3.1 Spatial distribution of the rain

Figure 1 gives the distribution of total rainfall and its standard deviation in April to June 2008. As shown in Figure 1a, rainfall above 1000 mm is mainly distributed in the coastal areas of southern Huilai and Yangjiang as well as the Pearl River Delta and rainfall above 1500 mm mainly concentrates in Haifeng, Huidong, Zengcheng, Zhuhai, Doumen and Shangchuan Island, with the island being the center of maximum rainfall of the province, at 1854.3 mm, the largest ever recorded in the same time of year since 1961. The second largest rainfall appeared in Haifeng, 1844.4 mm, which is in fact the third largest value

ever recorded over the same time since 1961. For the figure of anomaly percentages (omitted), rainfall is between 30% and 90% more in areas that receive more than 1000 mm and it is 50% to 100% more in the Pearl River Delta and areas to its two sides. Figure 1b shows the distribution of standard deviation of daily rainfall for each of the stations relative to the deviation of April to June mean. The standard deviation is basically consistent with the total rainfall, with the center of the standard deviation larger than 30 mm/d located on the southern coast of Huilai and Yangjiang as well as the Pearl River Delta.

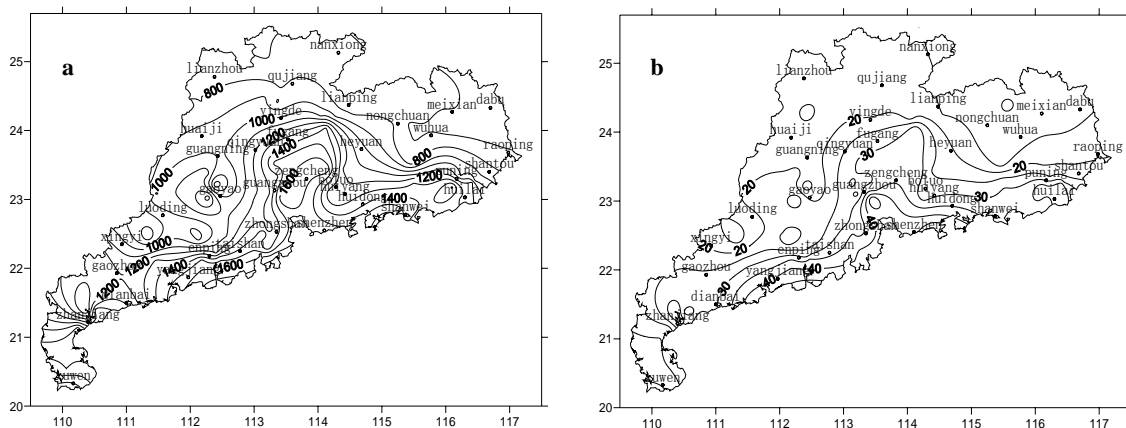


Figure 1. Distribution of total rainfall (a, units: mm) and standard deviation (b, units: mm/d) for April to June, 2008.

3.2 Low-frequency characteristics of the rainfall

Following Figure 1, 42 stations within the region which have the largest rainfall and variance are selected to represent the rainfall of Guangdong for its annually first raining season in 2008. Figure 2 gives the daily mean rainfall and its wavelet coefficient and wavelet power spectral analysis for these stations in April to June 2008. As shown in Figure 2a, five intense rainfall processes occurred during the raining season of 2008, in April 19-20, May 29-June 1, June 5-7, June 12-18, June 25-30, respectively, generally within the DBR period. In Figure 2b, there is significant periodic oscillation of quasi-7-12 days during the DBR time (from May 21 to June 20). Most of the periods pass the 0.05 significance test for the peak section of the DBR (June 5-18). Besides, significant quasi-single-weak oscillations exist from mid-April to late April and significant quasi-12-day oscillations are present even in late June when the DBR is over. Analyzing the wavelet power spectrum (shown in Figure 2c), we found that the primary period for the entire raining season is 9.5 days, basically consistent with the primary period for the DBR period.

3.3 Low-frequency characteristics of atmospheric circulation elements in the annually first raining season

Existing studies have shown that precipitation in the annually first raining season in the south of China is generated under some particular background of mid- and higher-latitudes and low latitudes, and each of the rain is usually accompanied with 500 hPa troughs in these latitudes, whose interaction results in intense rain^[30]. Besides, monsoonal surge from northern South China Sea moves northward to meet with cold air from the north, usually causing continuous heavy rain or basin-wide heavy rain that results in floods in the south of China^[23, 26, 31]. The amount of rain during the raining season is also related to the intensity of the southwesterly wind in the northern South China Sea (Liang et al.^[32]). Moreover, 500 hPa geopotential heights and 850 hPa winds are the two forecast fields for real-time medium-term numerical prediction that are referred to in operational forecasting. To improve the medium-term forecast of severe precipitation in Guangdong based on medium-term NWP products, we analyzed the periodic variation with time of 500 hPa geopotential heights averaged over the province (20°–25°N, 110°–117.5°E, see Figure 3) and 850 hPa zonal winds averaged over the northern South China Sea (15°–22.5°N, 110°–120°E, see Figure 4).

As shown in Figure 3, significant periodic oscillations of 5-15 days exist in the 500 hPa geopotential heights averaged over Guangdong and

periodic oscillations of quasi-8-13 days are also present during the severe DBR (May 21 to June 20). Especially, they all pass the 0.05 significance test during the strongest phase of the DBR (June 5-18). The finding is consistent with the periodic oscillations of quasi-7-12 days shown in the analysis above.

Besides, the areas of positive and negative 5-15-day wavelet coefficients for April, May and June are mostly corresponding to the time of less and more rain, respectively, suggesting close relationships between the quasi-periodic variation of precipitation in Guangdong and that of upper-level troughs above it.

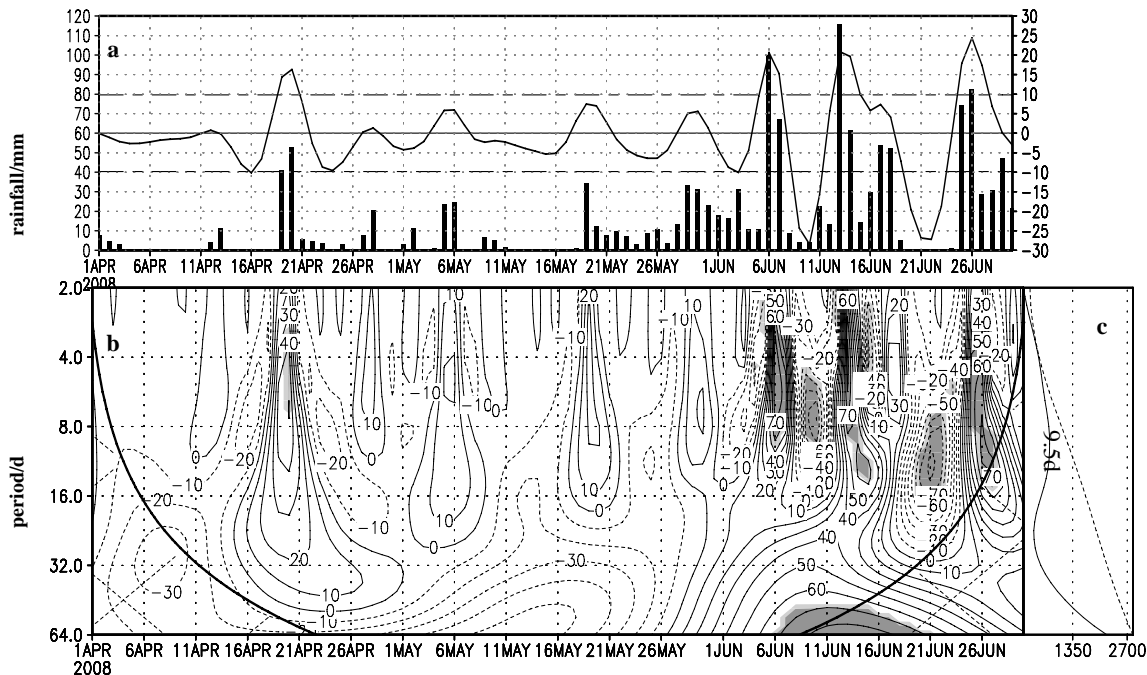


Figure 2. Day-to-day rainfall (a), its wavelet analysis (b) and wavelet power spectrum (c) for the 42 stations in Guangdong from April to June 2008. a: histogram for day-to-day rainfall, solid line for the time series of rainfall after 5-15 day filter, fine, dashed line for standard deviation of the time series of rainfall at 5-15 day frequency; b: shades for the area greater than the 0.05 significance level and the intersected areas on both sides indicate where the boundary effect is.

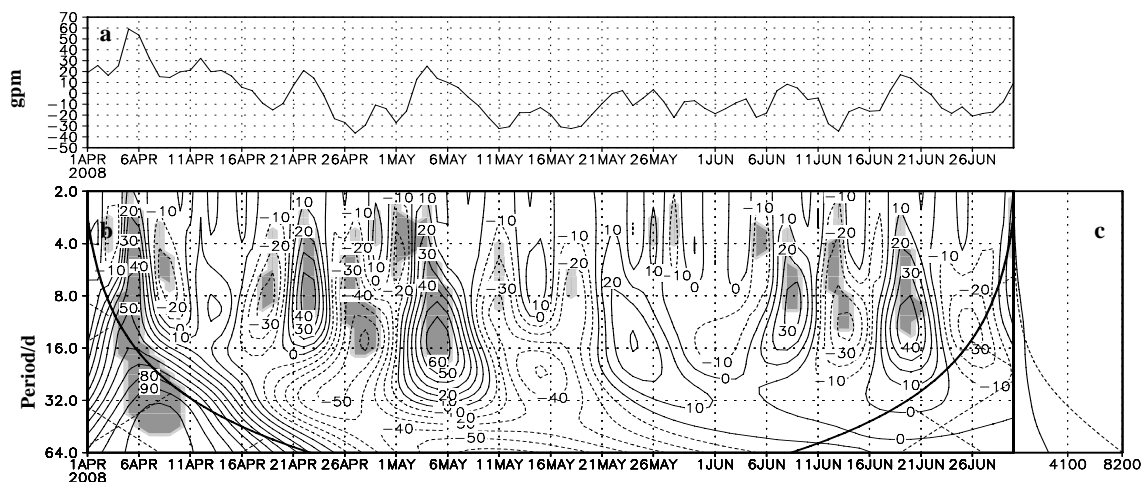


Figure 3. Same as Figure 2 but for the 500 hPa geopotential height field averaged over 20-25°N, 110-117.5°E (Units: gpm).

As shown in Figure 4, the 850 hPa zonal winds averaged over the northern South China Sea exhibit significant periodic oscillations of quasi-10-to-15 days and significant oscillations of quasi-12 days during DBR period, which passes the 0.05 significance test even during the peak of the DBR (June 5-18) and is consistent with those of quasi-7-to-12 days shown during the DBR.

Comparing Figure 2 with Figure 4, we found that the negative and positive wavelet coefficients for the 850 hPa zonal winds averaged over the northern South China Sea correspond well with the breaks and peaks of the precipitation. It also shows close correlation between the quasi-periodic variations of precipitation in Guangdong and quasi-periodic variations of 850 hPa zonal winds in northern South China Sea.

Besides, the 500 hPa geopotential heights averaged over Guangdong, as shown in Figure 3, present significant periodic oscillations of 8 to 15 days from April 16 to May 10, with corresponding wavelet coefficients being negative, positive, negative, and positive. Specifically, a negative center around April 19 was corresponding to a period of intense rainfall that appeared on April 19-20 (as shown in Figure 2) while a strong negative center around April 28 is corresponding to the rain break shown in Figure 2a. Comparing it with Figure 4a, we know that a positive center of quasi-8 days also exists around April 19 for the wavelet coefficient of 850 hPa zonal winds averaged over the northern South China Sea, or, it corresponds to the peak of the wind field in the northern South China Sea. In contrast, the wavelet coefficient for 850 hPa zonal winds, averaged for the

northern South China Sea on April 28, does not show a center of variation (Figure 4b). Correspondingly, the zonal winds (as shown in Figure 4a) are negative and relatively weak, suggesting a weak wind field in the northern South China Sea. It can then be said that the time around April 28 is with a strong negative center at the 500 hPa geopotential heights averaged over Guangdong, but it is corresponding to the break of the rain as the mean 850 hPa zonal wind is relatively weak in the northern South China Sea. It can also be determined that this zonal wind also experiences oscillations of quasi-8 days at the time around April 19 and near its peak value, which corresponds to a period of intense rainfall. However, as the zonal wind is much weaker than that during the DBR (Figure 4), the rainfall is quite intense but not as intense as that during the DBR.

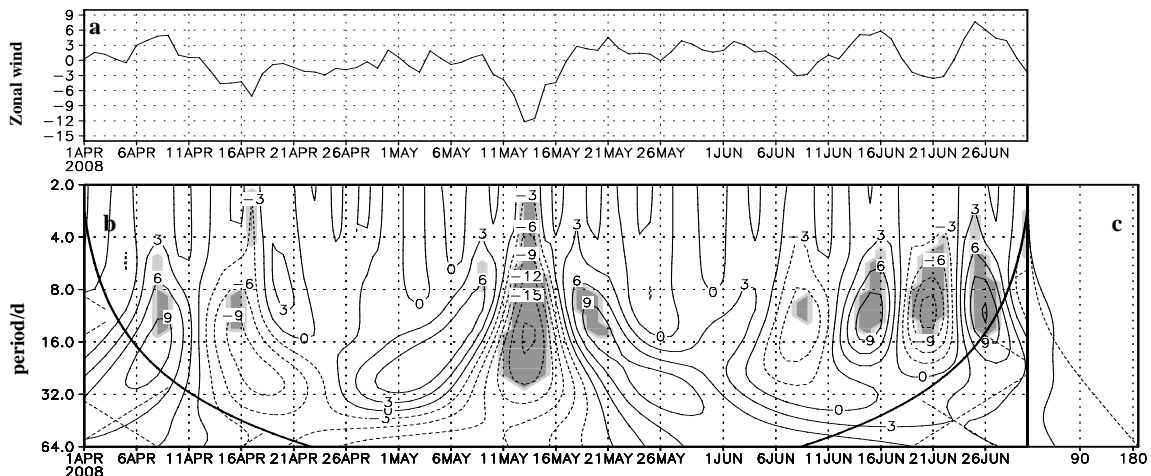


Figure 4. Same as Figure 2 but for the 850 hPa zonal wind averaged over the northern South China Sea (15-22.5°N, 110-120°E). Unit: m/s.

To understand more about the relationships between the variation of the rainfall in Guangdong and the 500 hPa geopotential heights averaged over the province and 850 hPa winds averaged over the northern South China Sea, filtering of 5 to 15 days is applied to them and the day-to-day precipitation averaged over 42 of the weather stations in the province (Figure 5). Phases are ahead of or lagged behind between these geopotential heights and winds and the rainfall, but the peak (valley) of post-filtering rainfall corresponds with the valley (peak) of the geopotential heights and the peak (valley) of the winds most of the time. Especially, the period of most intense DRB (June 12-18) is corresponding to a large negative phase of the geopotential heights and a large positive phase of the winds, while the rain break (May 19-23) is accompanied by the positive phase of the geopotential heights and the negative phase of the winds. Our finding is consistent with the result in Lin et al.^[2]—concluding from a diagnostic analysis on a rare DBR in 2008: each of the intense rains is

corresponding to the influence of a westerly trough, and the variation of maximum wind speed of low-level jet streams is in phase with the generation of a hard rain.

As is also shown in Figure 5, the filtered geopotential heights for both April 28 and May 11 are large valley values, though the rainfall field is much weakened as its corresponding wind field is also weak. As shown in our correlation analysis, the 5-to-15-day filter series of the day-to-day rainfall is correlated with the 500 geopotential heights and the zonal winds by coefficients of -0.36 and 0.60 . Although they both pass the 0.01 significance test, they are much more significantly correlated with the wind field than with the geopotential height field. It can then be concluded that the rainfall during the annually first raining season of Guangdong has the closest links with the monsoon in northern South China Sea, followed by the upper-level trough over the province. Heavy rainfall usually occurs when the upper-level trough is deep and the monsoon is strong. When a deep

upper-level trough is with significant monsoon, substantial rainfall occurs; when the upper-level trough is deep but the monsoon is insignificant, no

rainfall takes place in a significant way.

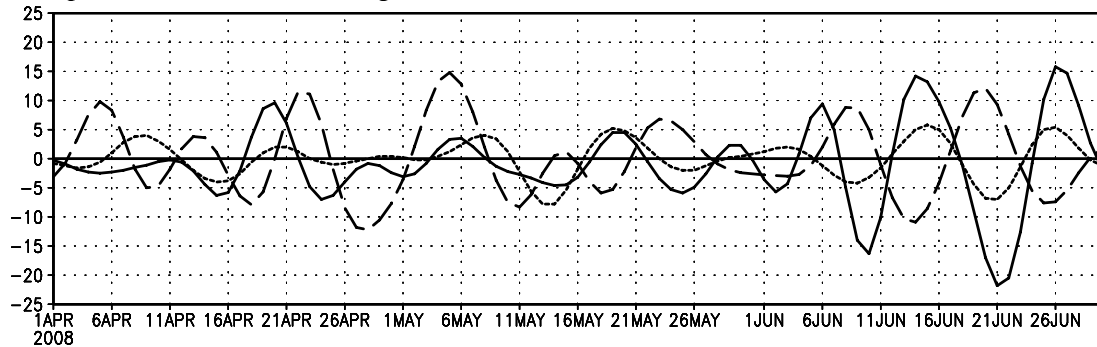


Figure 5. Filter of 5-15 days for precipitation anomalies averaged over 42 of Guangdong's weather stations (solid line, units: mm/d), anomalies of 500 hPa geopotential heights averaged over 20-25°N and 110-120°E (long dashed line, units: gpm), and anomalies of 850 hPa zonal winds averaged over 15-22.5°N and 110-120°E (multiplied by 2, short dashed line, units: m/s), for April to June 2008.

4 EFFECTS OF QUASI-10-DAY OSCILLATIONS OF MONSOON ON INTENSE DBR

As shown in Ju et al.^[33], the atmospheric intraseasonal oscillations (ISO) in the summer monsoon region of East Asia is propagated both meridionally and zonally; the former transport is mainly towards the north in the case of tropical ISO and towards the south in the case of ISO in the mid-and higher-latitudes, and the latter transport is mainly for the ISO to move eastward from its source in the Indian monsoon region and for the ISO to travel westward from its source in the western North Pacific. Both of the ISOs converge around 120°E to enhance

the ISO coming from the tropics, enabling it to continue its northward longitudinal advancement to pose some influence on the summer precipitation in the middle and lower reaches of the Yangtze River. As shown in the analysis above, the rainfall during the DBR in Guangdong has the closest link with the monsoon in northern South China Sea. How does the longitudinal and latitudinal propagation of the quasi-10-day oscillation of the monsoon during the DBR affect the rainfall?

A 5-15-day filter is conducted of the 850 hPa zonal wind averaged over 110-120°E for April to June, 2008 and its latitude-time cross section is studied (Figure 6).

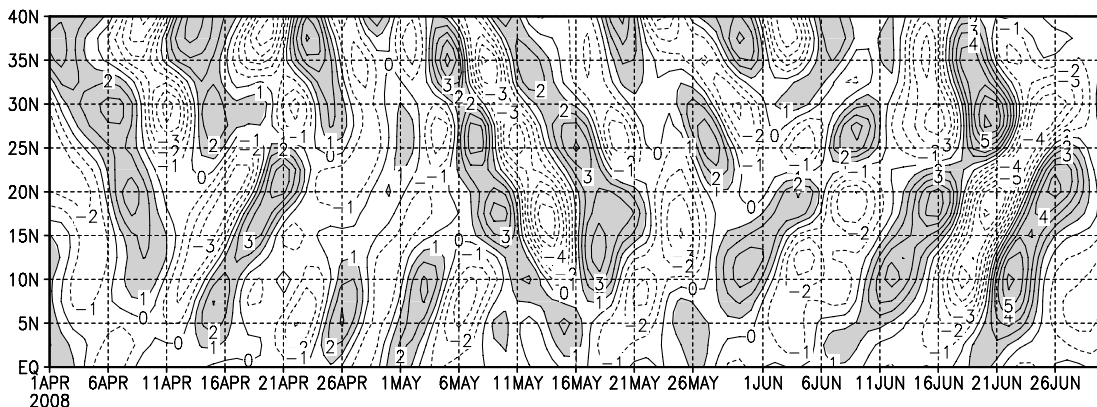


Figure 6. Latitude-time cross sections of low-frequency (5-15 days) 850 hPa zonal winds averaged over 110-120°E for April to June, 2008.

During the DBR (May 21 to June 20), low-frequency activities with a positive center experienced three transportations, with one of them being the mid-latitude westerlies traveling southward to 20°N and the other two being the South China Sea monsoon surge intensifying significantly in southern South China Sea and going northward to Guangdong and areas north of it, arriving at 20-25°N in late May,

early June and mid-June that correspond to the three processes of DBR (May 29 to June 1, June 5 to 7, and June 12-18).

A 5-15-day Lanczos filter is conducted of the 850 hPa zonal wind averaged over the northern South China Sea for April to June, 2008 and longitude-time cross sections are conducted (Figure 7). During the intense DBR from May 21 to June 20, low-frequency

activity had two processes of transport in late May and early June, moving westward from central Pacific near 180°. They arrived in northern South China Sea in early June and mid-June, corresponding to the two intense rains during the DBR in Guangdong. There are three westward transports starting from central Pacific, which have centers of significant positive values in 130-140°E. Located east of the Philippines, this region is where intense convection occurs and key to tropical cyclogenesis. According to Ju et al.^[33], this region could be a key to triggering intraseasonal oscillations.

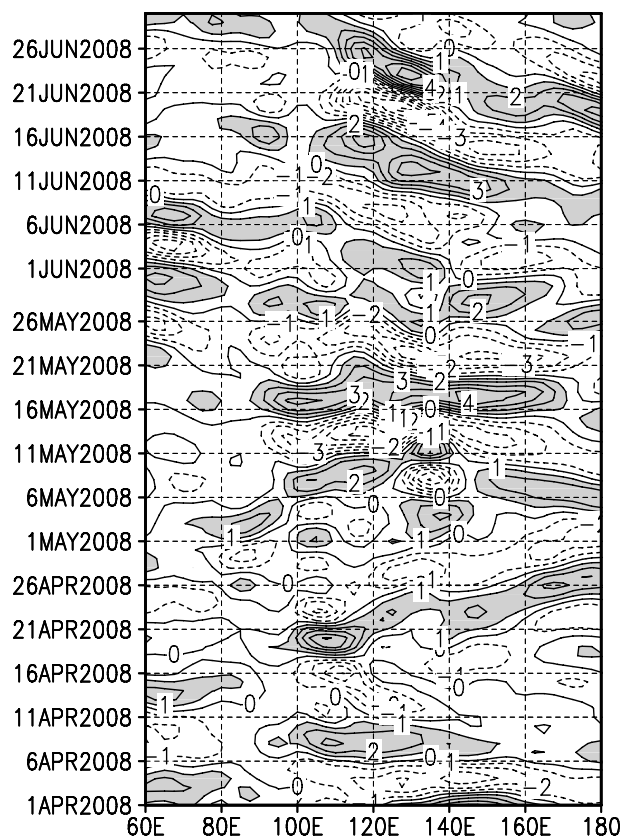


Figure 7. Longitude-time cross sections of low-frequency (5-15 days) 850 hPa zonal winds averaged over 15-22.5°N for April to June, 2008.

Combinations of Figure 6 with Figure 7 show that during the DBR, the two northward propagations of the zonal wind starting from the southern South China Sea are corresponding to two significant westward propagations originating from the central Pacific, reaching the northern South China Sea and Guangdong in early June and mid-June. It is then known that the quasi-10-day oscillation transporting westward from the central Pacific combines with the monsoon advancing northward from the southern South China Sea to result in the occurrence of monsoon surges, leading to the appearance of the two processes of intense DBR.

5 EVOLUTIONS OF QUASI-10-DAY

ATMOSPHERIC CIRCULATION FIELDS IN DIFFERENT PHASES DURING THE DBR

Following Mao et al.^[22], we studied the evolutions of quasi-10-day atmospheric circulation fields in different phases during the DBR in attempts to provide general guidance to intense rainfall, especially the DBR, based on medium-term NWP products.

First, a 5-15-day filter is applied to the day-to-day rainfall averaged for 42 weather stations in Guangdong in April to June, 2008 (Figure 2a). Then, the two processes of rainfall, whose amplitude of oscillation between the peak and valley during the DBR is larger than or equal to the standard deviation, are selected as two cycles of quasi-10-day: June 4-10 and June 10-22. Each of the cycles is divided into five phases (Figure 2a): phases 1 and 5 are the valley, phase 3 is the peak, and phases 2 and 4 are the transition phases. The five phases for the cycle of June 4-10 are corresponding to June 4, 5, 6, 8 and 10, and those for the cycle of June 10-22 are associated with June 10, 12, 13, 18, and 22. For phases 1 to 5 of the two cycles, composites are made of the 500 hPa geopotential heights, 850 hPa winds, vectors of water vapor flux, and divergence of water vapor flux, and the results are presented in Figures 8 and 9.

Figure 8 shows the geopotential heights at 500 hPa. At phase 1, the mid- and higher-latitudes are dominated by two troughs (over the Ural Mountains and Japan to the estuary of Yangtze River) and one ridge (over Lake Baikal and areas to its east). The subtropical high extends to 120°E, the isobaric contour of 584 dagpm was around 25°N, and the geopotential height was high and precipitation is weak over Guangdong. At phase 2, with the eastward movement of the trough over the Ural Mountains, the area north of Lake Balkhash to Lake Baikal is controlled by the troughs while the region north of the Yangtze's estuary to the northeast of China is affected by the ridge of the high pressure. At low latitudes, the subtropical high retreats to the part of West Pacific east of 130°E, a deepened upper-level trough is over northeastern India to most of the Chinese regions south of 30°N, the isobaric contour of 584 dagpm moves south to the coast of Guangdong, and precipitation begins to intensify in the province. At phase 3, Lake Balkhash to Lake Baikal is still an extensive region of troughs, though the westerlies south of it deepen and move to the east, steering weak cold air to the south. At low latitudes, the subtropical high intensifies a little and extends west though it stays generally in the part of West Pacific east of 125°E, a trough near the Bay of Bengal begins to deepen, an upper-level trough dominates from the Bay of Bengal to Guangdong, the isobaric contour of 584 dagpm is still over the coast of Guangdong, and

precipitation becomes the most intense in the province. At phase 4, the mid-latitude circulation becomes straight, the subtropical high intensifies and extends westward, the trough near the Bay of Bengal weakens, the isobaric contour of 584 dagpm pushes northward to areas north of 25°N, the geopotential heights rise over Guangdong and the precipitation weakens. The 850 hPa wind field is analyzed as follows. At phase 1, a southwesterly wind that forms from flows turning direction from the edge of the subtropical high (hereafter called "southwesterly wind_high") dominates the province while another southwesterly wind, which is weaker, originates from the Bay of Bengal and travels past the Indochina Peninsula (hereafter referred to as "southwesterly wind_bay"). At phase 2, the southwesterly wind_bay gradually intensifies and forms a weak cyclonic curvature over western Guangdong, Guangxi, Hunan and Guizhou, making Guangdong subject to it. Besides, the southwesterly wind_high also intensifies although it is mainly active along the southeast coast of the province. Due to the increased southwesterly wind and the presence of weak cyclonic convergence in western Guangdong, precipitation begins to get stronger in the province. At phase 3, the southwesterly wind_bay keeps intensifying and meets with weak cold air from the north to form significant cyclonic convergence over the mid-and lower-reaches of Yangtze and northwestern part of the south of China. Except for its southeastern coast which is controlled by the southwesterly wind_high, Guangdong is mainly under the prevalence of the southwesterly wind_bay, leading to intense precipitation during the DBR. At phase 4, as the southwesterly wind_bay weakens, the province becomes to be controlled by the increased southwesterly wind_high, resulting in the reduction of rain.

Figure 9 gives the distribution of composite 850 hPa fields from phases 1 to 4 of the vectors of water vapor transfer and divergence of water vapor flux during the two intense DRB rains in Guangdong. At phase 1, the transfer of water vapor is weak from both the subtropical high (hereafter called water-vapor transfer_high) and Bay of Bengal (hereafter referred to as water-vapor transfer_bay) so that all but the east part and Leizhou Peninsula is positive in terms of water vapor flux, i.e. in the diverging area of water

vapor. At phase 2, both the water-vapor transfer_bay and the water-vapor transfer_high intensify, the former mainly for the whole province and the latter mainly for its eastern part. The region of Guangdong and Guangxi as well as the middle and lower reaches of Yangtze become the diverging center of water-vapor flux, which also increases in intensity.

At phase 3, the water-vapor transfer_bay keeps intensifying and encounters weak cold air from the north over the middle and lower reaches of Yangtze River to form significant convergence of water-vapor flux, resulting in the convergence concentrated over the lower reach of the Yangtze and Guangdong, turning the province into a zone of consistent convergence of water vapor. As high-value areas of water-vapor flux are mainly concentrated on the coast of the south of China, intense DBR takes place on the coast of southern part of Guangdong and Pearl River Delta. At phase 4, as the transfer from the Bay of Bengal weakens, water vapor originating from the edge of the subtropical high becomes dominant so that all but the eastern part is with the convergence of water-vapor flux and the precipitation weakens. As shown in an existing study^[2], the water vapor that supplies most of the basin-wide hard rains during the annually first rainy season mainly originates from the Bay of Bengal and goes past the Indochina Peninsula. Apparently, it was due to the convergence between the intensifying warm and moist air from the southwesterly wind over the Bay of Bengal and the weak, southward-going cold air that the two processes of intense rain took place during the DBR.

As a mid-latitude trough deepens near the Ural Mountains and a westerly trough deepens and moves eastward south of Lakes Balkhash and Baikal, weak cold air is channeled southward. At low latitudes, the subtropical high is weak and eastward, making most of China (south of 30°N) in the control of a deepening upper-level trough. Meanwhile, the trough over the Bay of Bengal keeps deepening, intensifying the warm and moist southwesterly that turns from the bay and merging with the weak cold air over the lower reach of the Yangtze and south of China. As a result, water-vapor flux converges there to result in intense precipitation during the DBR.

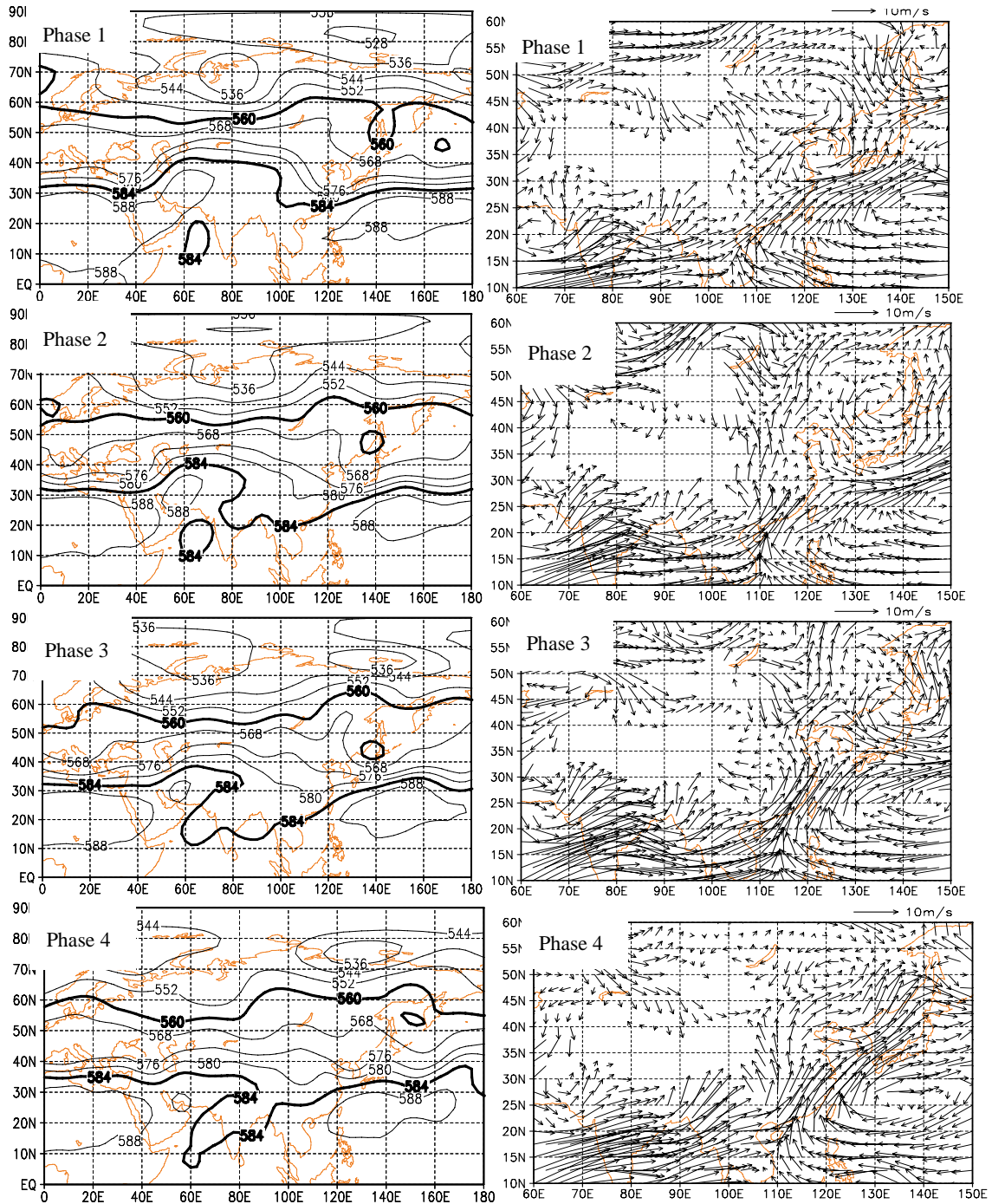
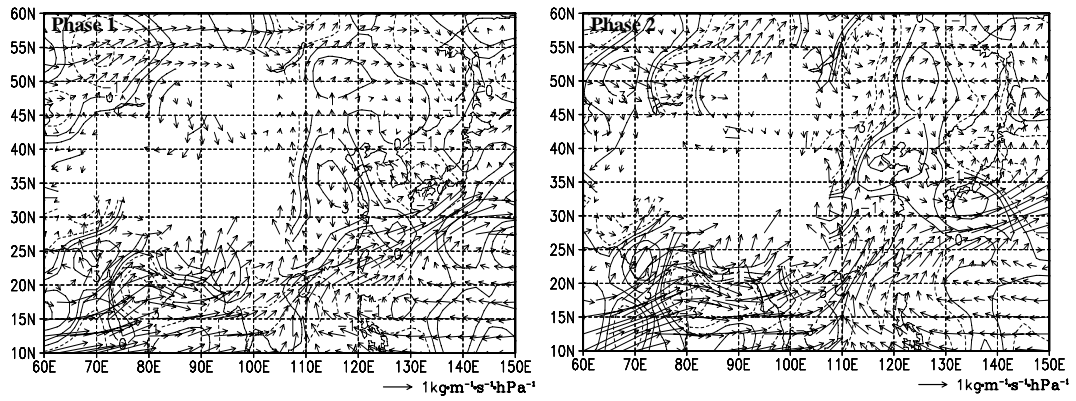


Figure 8. Composite fields of phases 1 to 4 for 500 hPa geopotential heights (left panel, unit: dagpm) and 850 hPa winds (right panel, unit: m/s) for the two intense rains during the DBR of 2008 in Guangdong.



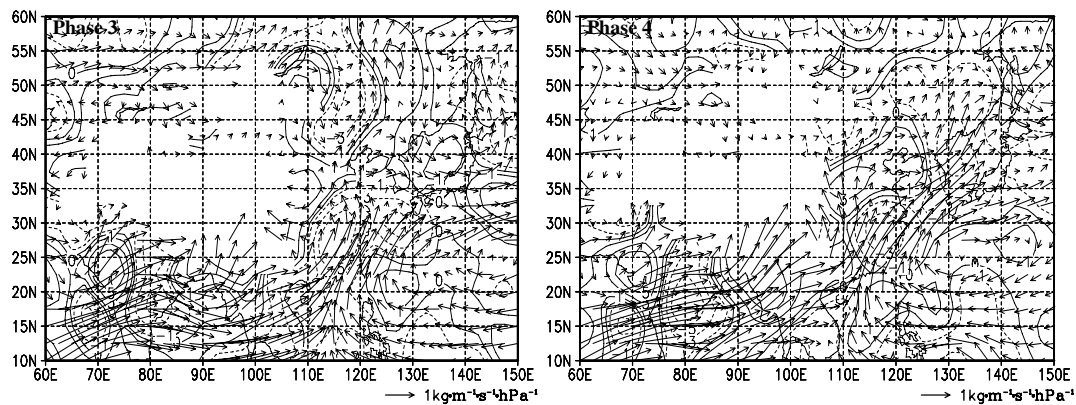


Figure 9. Composite fields of phase 1 to 4 for vectors of water-vapor transport (unit: kg/hPa m s) and divergence of water-vapor flux (unit: $10^{-7} \text{ kg}/(\text{hPa m}^2 \text{ s})$) for the two intense rains during the DBR of 2008 in Guangdong at 850 hPa.

6 CONCLUSIONS

(1) As shown in our wavelet analysis, oscillations of quasi-7 to 12 days (or quasi-10 days), 8 to 13 days, and quasi-12 days are significant in the day-to-day precipitation, 500 hPa geopotential heights and 850 hPa zonal winds, during the DBR. As shown in our correlation analysis, the precipitation in Guangdong's annually first rainy season is most correlated with the monsoon in northern SCS, followed by the upper-level trough over Guangdong. A deepened upper-level trough and intensified monsoon are usually associated with heavy rainfall while a deep upper-level trough and insignificant monsoon are accompanied with insignificant precipitation.

(2) As shown in our analysis of the meridional and zonal transport of the quasi-10-day oscillation of the zonal wind during the DBR, the quasi-10-day oscillation transporting westward from the central Pacific strengthens over an area of intense convection east of the Philippines and merges with the monsoon that transports northward from southern SCS and strengthens. As a result, a strong monsoon surge occurs to result in two processes of intense rain.

(3) Using composite analysis based on typical phases, we studied the evolutions of the above oscillation that are common for different phases of atmospheric circulation. With the eastward propagation of a mid-and higher-latitude trough over the Ural Mountains and the deepening and eastward propagation of the westerly trough south of Lakes Balkhash and Baikal, weak cold air is steered southward. At low latitudes, the subtropical high is weak and eastward, and an upper-level trough gradually controls most of the Chinese regions that are south of 30°N , while the trough over the Bay of Bengal keeps deepening to increase the southwesterly warm and moist airflow that turns from the Bay of Bengal, which forms significant convergence of water vapor flux by joining the southward-going weak cold

air over the lower reach of Yangtze and south of China, resulting in intense rainfall during the DBR.

REFERENCES:

- [1] Editorial Team. Handbook for Operational Climate Techniques [M]. Beijing: China Meteorological Press, 2008: 42-44.
- [2] LIN Liang-xun, WU Nai-geng, HUANG Zhong, et al. Causality Analysis of the Infrequent Dragon-Boat Precipitation in Guangdong Province in 2008 [J]. Meteor. Mon., 2009, 35(4): 43-50.
- [3] MADDEN R A, JULIAN P R. Detection of a 40~50 day oscillation in the zonal wind in the tropical Pacific [J]. J. Atmos. Sci., 1971, 28(5): 702-708.
- [4] MADDEN R A, JULIAN P R. Description of globe scale circulation cells in the tropics with 40~50 day period [J]. J. Atmos. Sci., 1972, 29(6): 1109-1123.
- [5] LAU K M, YANG G J, SHEN S H. Seasonal and intraseasonal climatology of summer monsoon rainfalls over East Asia [J]. Mon. Wea. Rev., 1988, 116(1): 18-37.
- [6] MIAO Jin-hai, LAU K M. Low Frequency Oscillation (30-60 day) of Summer Monsoon Rainfall over East Asia [J]. Chin. J. Atmos. Sci., 1991, 15(5): 65-71.
- [7] MO K C. Intraseasonal modulation of summer precipitation over North America [J]. Mon. Wea. Rev., 2000, 128(5): 1490-1505.
- [8] JONES C. Occurrence of extreme precipitation events in Californian and relationships with the Madden-Julian Oscillation [J]. J. Climate, 2000, 13(20): 3576-3587.
- [9] KRISHNAMURTHY V, SHUKLA J. Intraseasonal and interannual variability of rainfall over India [J]. J. Climate, 2000, 13(24): 4366-4377.
- [10] CHEN Tsing-chang, WANG Shih-yu, HUANG Wan-ru, et al. Variation of the east Asian summer monsoon rainfall [J]. J. Climate, 2004, 17(4): 744-762.
- [11] KRISHNAMURTHY V, SHUKLA J. Intraseasonal and seasonally persisting patterns of Indian monsoon rainfall [J]. J. Climate, 2007, 20(1): 3-20.
- [12] HOYOS C D, WEBSTER P J. The role of intraseasonal variability in the nature of Asian monsoon precipitation [J]. J. Climate, 2007, 20(17): 4402-4424.
- [13] HUANG Fei, HUANG Shao-Ni, ZHANG Xu. Study on the Climatological Intraseasonal Oscillation of Chinese Rainfall. Periodical of Ocean University of China [J]. 2008, 8(2): 173-177.

- [14] YANG Guang-Ji. The Characteristics of Low Frequency Oscillation about Rainfall and Wind Disturbances over Eastern China [J]. *Chin. J. Atmos. Sci.*, 1992, 16(1): 103-110.
- [15] ZHOU Bing, WEN Ji-fen. Abnormality of Summertime Precipitation of Eastern China and General Circulation with LFO in 1998 [J]. *Quart. J. Appl. Meteor.* (in Chinese), 2006, 17(3): 129-136.
- [16] JU Jian-hua, SUN Dan, LU Jun-mei. The Influence of the East Asian Monsoon Stream on the Large-Scale Precipitation Course in Eastern China [J]. *Chin. J. Atmos. Sci.*, 2007, 31(6): 1129-1139.
- [17] YANG Xin-jie, LUO Jian, QIAO Jin-ming, et al. The heavy rainfall over the Jianghuai basin and the 20-25 days low frequency oscillation in 1991 [J]. *Sci. Meteor. Sinica*, 1994, 14(4): 354-361.
- [18] CHEN Li-zhen, ZHANG Xian-gong, CHEN Long-xun. A Study of the Difference of low-frequency Oscillation between the Typical Flood/Drought years in Changjiang Valley [J]. *Quart. J. Appl. Meteor.* (in Chinese), 1994, 5(4): 483-488.
- [19] LU Er, DING Yi-hui. Low Frequency Oscillation in East Asia during the 1991 Excessively Heavy Rain Over Changjiang-Huanghe River Basin [J]. *Acta Meteor. Sinica* (in Chinese), 1996, 54(6): 730-736.
- [20] YANG H, LI C Y. The relation between atmospheric intraseasonal oscillation and summer severe flood and drought in the Changjiang-Huanhe river basin [J]. *Adv. Atmos. Sci.*, 2003, 2(4): 540-553.
- [21] JU Jian-hua, ZHAO Er-xu. Impacts of the low frequency oscillation in East Asian Summer Monsoon on the Drought and Flooding in the Middle and Lower Valley of the Yangtze River [J]. *J. Trop. Meteor.* (in Chinese), 2005, 21(2): 163-171.
- [22] MAO Jiang-yu, WU Guo-xiong. Intraseasonal Variability in the Yangze-Huaihe River rainfall and subtropical high during the 1991 Meiyu period [J]. *Acta Meteor. Sinica* (in Chinese), 2005, 63(5): 762-770.
- [23] SHI Xue-li, DING Yi-hui. A study on extensive heavy rain processes in South China and the summer monsoon activity in 1994 [J]. *Acta Meteor. Sinica* (in Chinese), 2000, 58(6): 666-678.
- [24] XIN Fei, XIAO Zi-niu, LI Ze-chun. Relation between flood season precipitation anomalies in South China and East Asian atmospheric low frequency oscillation in 1997 [J]. *Meteor. Mon.*, 2007, 33(12): 23-30.
- [25] TONG Tian-yi, WU Chi-sheng, WANG An-yu, et al. An observational study of intraseasonal variations over Guangdong province China during the rainy season of 1999 [J]. *J. Trop. Meteor.* (in Chinese), 2007, 23(6): 683-689.
- [26] TAO Shi-yan, WEI Jie. Correlation between monsoon surge and heavy rainfall causing flash-flood in southern China in summer [J]. *Meteor. Mon.*, 2007, 33(3): 10-18.
- [27] GU De-jun, WANG Dong-xiao, JI Zhong-ping, et al. New research on cone of influence and computing scheme of Mexican hat wavelet transform [J]. *Quart. J. Appl. Meteor.* (in Chinese), 2009, 20(1): 62-69.
- [28] DUCHON C E. Lanczos filtering in one and two dimensions [J]. *J. Appl. Meteor.*, 1979, 18(8): 1016-1022.
- [29] ZHANG Teng-fei, LU Ya-bin, ZHANG Jie. Contrast analysis of 4 heavy snow events in Yunnan since 2000 [J]. *Quart. J. Appl. Meteor.* (in Chinese), 2007, 18(1): 64-72.
- [30] ZHU Qian-gen, LIN Jin-rui, SHOU Shao-wen, et al. The Principles and Methods of Synoptics (Edition Four) [M]. Beijing: China Meteorological Press, 2007: 347.
- [31] LIN Ai-lan, LIANG Jian-yin, LI Chun-hui, et al. Monsoon circulation background of '0506' continuous rainstorm in south China [J]. *Adv. Water Sci.*, 2007, 18(3): 424-432.
- [32] LIANG Jian-yin, WU Shang-sen. Variations of rainfall anomalies in Guangdong associated with summer monsoon [J]. *J. Trop. Meteor.* (in Chinese), 1999, 15(1): 38-47.
- [33] JU Jian-hua, SUN Dan, LU Jun-mei. The relay character analysis of the zonal and longitudinal propagations of the atmospheric intraseasonal oscillation in the East Asian monsoon region [J]. *Chin. J. Atmos. Sci.*, 2008, 32(3): 523-529.

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