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ASYMMETRIC DISTRIBUTION OF CONVECTION ASSOCIATED WITH TROPICAL CYCLONES MAKING LANDFALL ON THE EAST CHINA COAST

ZHU Pei-jun (朱佩君)[1], ZHENG Yong-guang (郑永光)[2], ZHENG Pei-qun (郑沛群)[3]

(1. Department of Earth Sciences, Zhejiang University, Hangzhou 310027 China; 2. National Meteorological Center, Beijing 100081 China; 3. Zhejiang Province Meteorological Bureau, Hangzhou 310017 China)

Abstract: The asymmetric distribution of convection associated with tropical cyclones making landfall on the east China coast is studied with black-body temperature (TBB) data from Fengyun-2 (FY-2) geostationary weather satellite. The convection in various quadrants of the TCs is examined for the period of −24 to 6 h relative to landfall. The convection to the southern side of the TCs was much more intense than that to the northern side during the whole landfall period. The convection to the western side of the TCs was stronger than that to the eastern side for the time −8 h before and at the landfall. After landfall, the situation reverses. The asymmetric convection of the TCs was partly due to the vertical wind shear and storm motion, and partly because the process of landfall restrained the convection in relevant quadrants. Besides, the orographic uplift along the east of China was favorable to the enhancement of convection in the eastern side of the TCs. From the characteristics of convective asymmetry of the TCs landing on the south and east of China, it is known that their main difference might be the included angle between the TC path and the coastline as well as the terrain along the coast.

Key words: landing typhoons; asymmetric convection; TBB; east of China

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1 INTRODUCTION

High winds, intense rainfall and storm surges triggered during the landfall of TCs impose disastrous damages to the coastal regions and result in enormous economic losses. Due to the differences in atmospheric environment in high latitudes and the effect of underlying surface, the TC undergoes significant changes in structure and intensity during landfall. Due to the forcing effect of mountain ranges, as pointed out by Chen et al.[1], rainfall increases to the north of a landing TC in the east of China, contributing to asymmetric distribution of rainfall over the north and south part of the TC. Being an atmospheric environment factor for asymmetric convection distribution in TCs, vertical wind shears are responsible for the asymmetric distribution of vertical motion[1]. For the inner core of the TC, vertical wind shear makes it likely that convection, under the condition of dry adiabatic conditions, appears downshear to its right[2-4]. By contrast, intense convection tends to occur downshear and to its left in the case of wet adiabatic processes and observational studies[5-8]. There has been little observational work on the asymmetric distribution of convection including the outer core of TCs. As shown in the study about the effect of vertical wind shear on the distribution of lightning in TCs (Corbosiero et al.[5]), the most flashes occurred downshear right, and the greater the magnitude of vertical shear, the more likely it deflects to the right. In addition, previous observational and numerical studies have shown that the motion of TCs is also responsible for asymmetric distribution of the convection[9-12]. Intense convection usually takes place in the front quadrant of a moving TC, especially so with fast-moving TCs, attributable to the asymmetricity in boundary-layer friction caused by TC motion. In a numerical experiment by Shapiro et al.[9], boundary-layer convergence concentrates in the front of slow-moving TCs (<5 m/s) while confining to the right front quadrant with fast-travelling ones (>10 m/s).

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Biography: ZHU Pei-jun, associate professor, primarily undertaking research on landfalling tropical cyclones.
Corresponding author: ZHU Pei-jun, e-mail: zhupj@zju.edu.cn

With various factors interacting with each other, landfalling TCs show complicated characteristics more significantly. Due to the forcing of mountain ranges in the south of China, both the area and intensity of heavy rain are more obvious to the east of the TC than to the west of it[1]. Because of the vertical wind shear and TC motion, convection is intensified at the middle and lower levels of a landing TC[13, 14]. Besides, asymmetrically distributed water vapor flux, low-level horizontal wind shear, and convergence / divergence are also contributing to asymmetric distribution of convection. As shown in numerical experiments[17-19], the change in the preferred area of rainfall related to landfalling TCs is associated to that of water vapor flux, vertical static stability and surface roughness.

The east of China is next to the south of China in terms of the frequency of TC landfall[20]. How does their convection distribute? As shown in studies of the TBB contours of the TCs making landfall in the east of China in the past few years, the convection at the time of landfall shows significant asymmetric distribution. Then, how does the convection of these TCs evolve and what is behind the evolution? How are these TCs different from those landing in the south of China and what are the main reasons? These are all the issues this work is going to address.

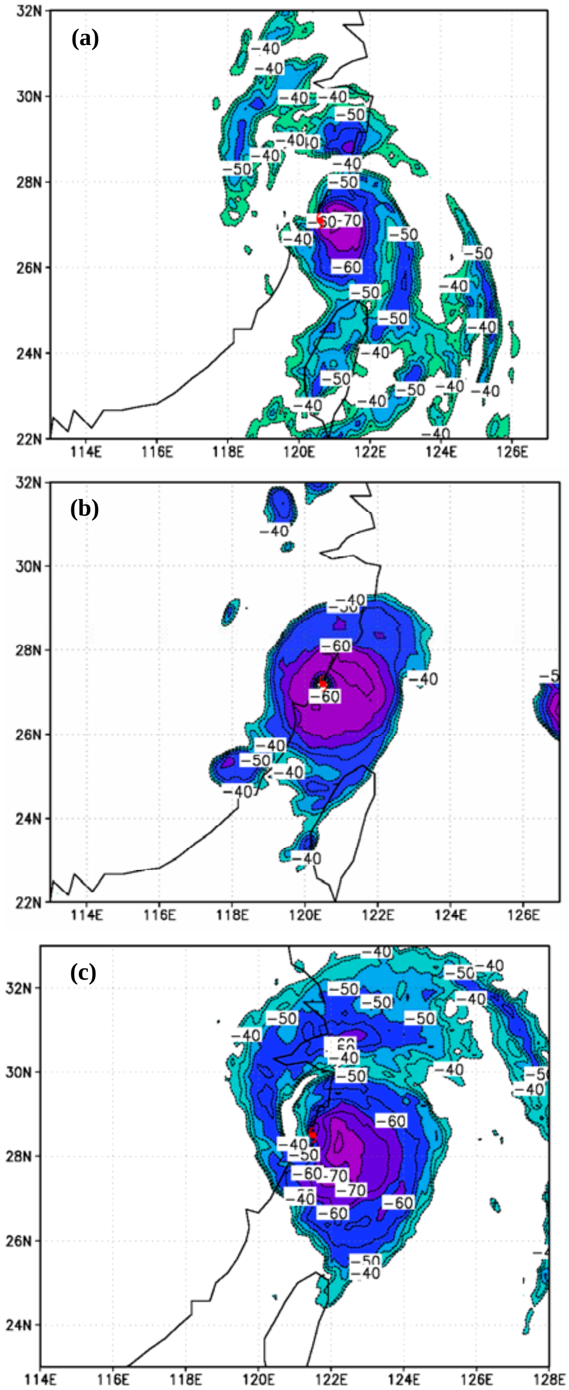
2 DATA AND METHODS

2.1 *Cases*

TCs Wipha, Saomai, Khanun and Matsa, which made the first landfall from 2005 to 2008 on the coast of the east of China, were selected in this work. They were all captured by the FY-2C weather satellite. See Table 1 for their general description. Significant asymmetricity is shown by the distribution of their TBB contours at landfall (Figure 1). Their tracks are shown in Figure 2. Going on northwest tracks, all of the TCs made landfall on the coast of central and southern Zhejiang province. As shown in Figure 2, the angle is nearly 90° between the direction of TC motion and the coastline. Though with limited cases of landfall for this part of the coast (one TC per year on average), serious economic losses were brought about to the provinces and cities affected (Table 1).

Table 1. Cases of TCs and their general information.

Serial No.	Name	Time (BST) and site of landfall in Zhejiang (BST)	Direct economic losses(for Zhejiang, unit: billion RMB)
0713	Wipha	9.19.02:30 Cangnan	56.2
0608	Saomai	8.10.17:25 Cangnan	127.37
0515	Khanun	9.11.14:50 Taizhou	79.5
0509	Matsa	8.6.03:40 Yuhuan	89.11



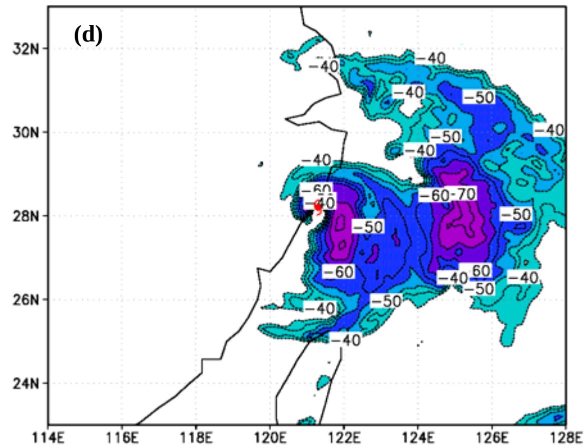


Figure 1. Distributions of TBB contours at landfall of TCs Wipha (a), Saomai (b), Khanun (c) and Matsa (d).

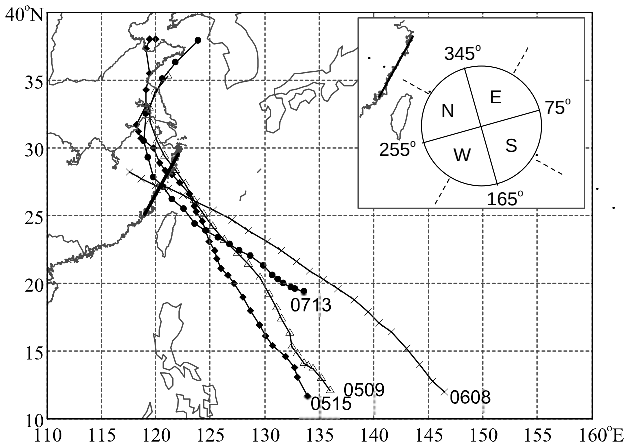


Figure 2. Moving tracks of the TCs.

2.2 *Data*

Continuous data for the life cycle of TCs provided by geostationary weather satellites are high in time and space resolution and cover large area. To illustrate the convection distribution over an extended period of time around landfall, the FY-2C satellite blackbody brightness temperature (TBB) data was used for the analysis. The time and space resolutions of the data are 1 h and 0.1° ×0.1° respectively. The period of time chosen for the analysis spans from 24 hours before landfall to 6 hours after it, denoted in the text as −24 h to 6 h, relative to the time of landfall. For studies on the intensity of convection using satellite TBB data, special caution should be kept in mind: low-value TBB could arise from either convective clouds, or the canopy of convective clouds being advected by wind, or simply some upper cirrus. Nevertheless, the low TBB account for a form of upper-level convection[13]. Besides, to investigate into the causes for the asymmetric distribution of TC convection, the 6-hourly 1° ×1° reanalysis data from National Centers for Environmental Protection (NCEP, USA) are used to determine the vertical wind shear, and the hourly TC positioning data from National Meteorological Center are used to obtain the TC motion at various points of time.

2.3 *Methods*

To account for the asymmetricity, convection in the eastern and western quadrants as well as the northern and southern quadrants of the TC is compared. Besides, to compare with the convection of TCs in the south of China, a method of Chan et al.[13] for dividing TC quadrants is used in this work. In other words, each of the 1/4 quadrants is determined relative to the coastline where the landfall takes place. As the coastline in southeast China shows an included angle of about 30° with the true north (as indicated by the solid line in Figure 2), the northern quadrant lies within an area between 255° and 345°, the eastern quadrant between 345° and 75°, the southern quadrant between 75° and 165°, and the western quadrant between 165° and 255°. To have a more accurate description of the relationships between the convection and the vertical wind shear and TC motion, each of the 1/4 quadrants is further divided into two 1/8 quadrants, with the 1/8 quadrant in the right of the northern quadrant denoted as quadrant No.1, which covers the range from 300° to 345°, followed by quadrant No.2, 3, … 8, each covering 45°. To explain how convection behaves over the regions (including the TC outer core), a relatively large radius is used where R=40 units of TBB gridpoints. TBB values are averaged for individual regions to determine the relative intensity of convection in various quadrants.

To compute the vertical wind shear in a TC environment, the NCEP 1°×1° reanalysis is used. Wind vectors in the 11×11 gridpoints centered on the cyclone center for 200 hPa and 850 hPa levels are selected to derive the average vertical shear. To obtain relatively stable moving direction and speed of the TC, 6-hourly changes in TC position are selected over the period from −24 h to 6 h. All together, the moving direction and speed are known for a total of five sections of landfall.

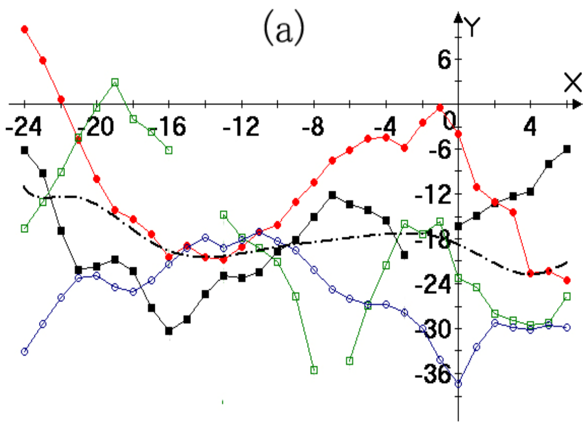
Unless specified otherwise, the values taken for the environmental vertical wind shear, TC moving direction and division of TC quadrants are all relative to the coastline.

3 BASIC CHARACTERISTICS OF CONVECTION ASYMMETRICITY

Subtracting the northern quadrant from the southern one clearly shows the asymmetricity of convection for them. After averaging the data of all cases, basic convection contrasts between the northern and southern parts of the TC can be determined

(Figure 3a). As shown in the averaged TBB curve, the convection is always stronger in southern than in the northern part of the TC over the 30 hours around landfall. Before −20 h, the TBB difference stays around −11°C. Afterwards, differences between the two parts begin to increase and fluctuate with time between −16°C and −24°C, reaching the maximum first at −14 h and then at 4 h while hitting the minimum at −4 h. For the individual TC cases, the convection difference are more evident as shown in figure 3a. For the time of the extremum occurrence, all but Saomai differ much from the mean result, though with similar evolution with time: north-south convection contrasts have their minimum at or prior to −20 h, increase afterwards, decrease prior to landfall, and increase again at or after landfall.

Similarly, the mean TBB difference curve, obtained by subtracting the western quadrant from the eastern one, shows that the convection in the eastern and western parts of the TC undergoes a transitional process during the landfall. Convection is stronger in the western than in the eastern part of the TC during the time from −24 h to −8 h. After landfall (at 4 h), the convection contrasts acquire the maximum between the two parts of the TC. For each of the cases, the curves vary consistently with the mean result, like Wipha and Matsa, though differ in the amplitude of asymmetricity. For Saomai, convection becomes stronger in the eastern than in the western part only between 2 to 5 h after landfall; for Khanun, convection is generally symmetric in the east-west direction prior to −10 h while being as much as −30°C more intense in the eastern than in the western part afterwards.



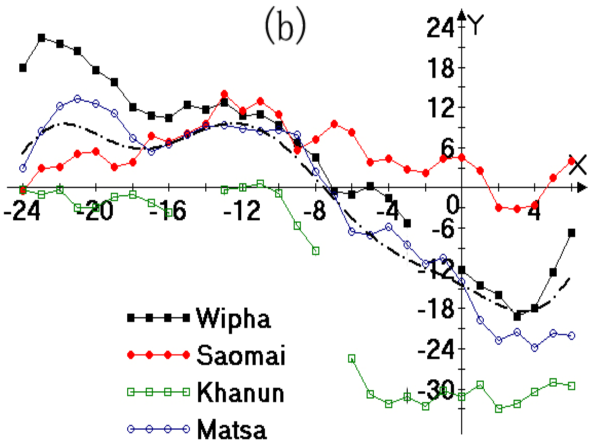


Figure 3. Differences of mean TBB between the southern and northern quadrants (a) and between the eastern and western quadrants (b). The dotted and dashed line is for the smooth curve of averages and the abscissa is the relative time of TC landfall in the unit of hour. Negative (positive) values indicate the time prior to (after) landfall. The ordinate is for the TBB differences in the unit of °C.

4 ANALYSIS OF IMPACT FACTORS

As shown in the analysis of the previous section, the southern and western quadrants have more active convection than in the other two quadrants prior to landfall while the eastern quadrants have more active convection around landfall, altering the asymmetric features. To explain the causes for such asymmetric distribution and evolution of the convection, this work studies the factors related to the vertical wind shear and TC motion as well as the land effect are analyzed as follows.

4.1 *Vertical wind shear and TC motion*

To illustrate the effect of vertical wind shear and TC motion on the distribution of convection, a statistical analysis was conducted with data of all times for the TC cases above (Figure 4). During the analysis, all of the vertical wind shear and TC motion are unified to a single direction. Then, the TBB data are rotated around the TC center accordingly. After that, the averaged TBB is statistically determined for the individual 1/8 quadrants relative to the unified vector direction. As this study is focus on the asymmetricity of convection, only gridpoints for which TBB≤−32°C will be included in the statistics. Taking into account the vertical wind shear and TC motion in the real environment (Figures 5a, 5d, 5g, and 5j), the magnitude of vertical wind shear and TC motion from 3 to 7 m/s is analyzed respectively. Figure 4 gives the result for vertical winds shear of moderate to high strength (⩾ 5 m/s) and TC motion of moderate to high speed (⩾ 3 m/s). As is shown, the highest number of gridpoints where convection is most likely to occur concentrate over downshear left , i.e., quadrants No.7 to No.8 and No.1, which are indicated by the dashed line relative to the direction of the unified vector (Figure 4a) and associated with the smallest regionally averaged TBB values. The opposite is true for the quadrants with the least likely occurrence of convection, which are quadrants No.3 to No.5 and with the largest number of mean TBB values. It is consistent with previous observational and numerical studies with moist physics[5-8]. Convection occurs mainly to the right and rear of the moving direction of the TC, i.e., in quadrants No.3 to No.5, as shown in the dashed line in Figure 4b (The preference of convection is mainly in quadrants No.4 to No.6 when moving speed exceeds 6 m/s), However, minimum mean TBB occurs in quadrants No.4 to No.6, suggesting confined but intense convection in quadrant No.6. The quadrants in which convection is most unlikely to occur are No.7 to No.8 and No.1, which are also with maximum TBB. Compared with previous studies, results here shift slightly to the right of the moving direction. However, asymmetric convection resulting from TC motion differs with various parts of the TC, as indicated in the previous studies. In the inner core of the TC, convection is likely to take place ahead of or to the left of its motion, a result that arises from high-speed cyclonic rotation of the inner-core air. Over the outer core of the TC—an area of larger radius, convection tends to occur in front of or to the right of the TC motion, even in the rear and right of the TC motion, which is associated with the asymmetric friction and convergence resulting from the motion of the TCs[9-12]. The results of this study—shifting more to the right of the previous findings—may result from computations for relatively large radii. A similar analysis of low-level divergence fields (figure omitted) shows that low-level convergence is consistent with the area of concentrated convection that is associated with the TC motion. Similar results are presented in Li et al.[22] who conducted numerical modeling of Typhoon Rananim (2004) that made landfall in the same region. Intense convection of the eyewall is mainly located in the southeastern side (which corresponds to the southern by west side of the TC in this study) and asymmetric distribution of the convection is also related to the pattern of divergence resulting from the asymmetric distribution of airflow relative to the TC.

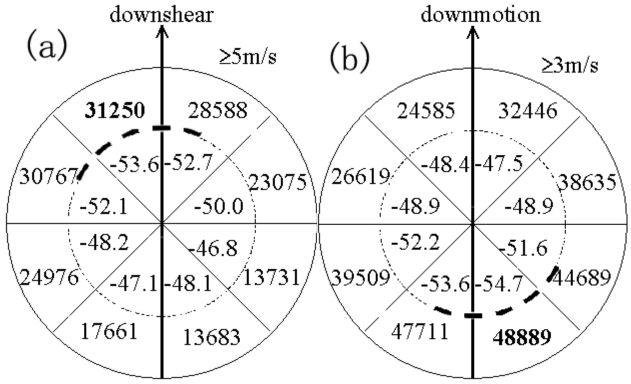


Figure 4. Effect of vertical wind shear (a) and TC motion (b) on the distribution of convection. The quadrant that includes the dashed line is where convection is likely to occur. Numerals of the inner and outer circles stand for the mean TBB and the numbers of gridpoint for TBB ≤−32°C respectively in the 1/8 quadrant.

Based on the vertical wind shear and TC motion and their effect on the distribution of convection, the areas can be identified where convection is likely to occur in association with the temporal variation of the TC. They are then compared with the actual distribution of mean TBB (Figure 5). Figures 5a, 5d, 5g, and 5j are for the wind shear and TC motion of Wipha, Saomai, Khanun and Matsa, respectively, and what are shown on the curves are the directions relative to the coastline of the east of China. In particular, the arcs in Figures 5b, 5e, 5h and 5k are for the quadrants in which convection is likely to occur relative to the coastline, and the outward (inward) solid (dashed) arcs stand for the quadrants where convection is likely to take place as a result of time-dependent vertical wind shear (TC motion), and their time is corresponding to that of the left panel. Figures 5c, 5f, 5i and 5l are for the TBB averaged for each of the 1/8 quadrants, which also evolves with time.

As shown in the curves of each of the TC studied, vertical wind shear takes place in quadrants approximately opposite to those of the TC moving direction by a chance of 70%, i.e., they differ in direction by as much as 180°±45°, making it more likely for convection to appear in generally consistent quadrants (as shown in Figures 5b, 5e, 5h and 5k), i.e., in quadrants No.4 and No.5, resulting in more significant convection in the south than in the north of the TC. It is evident in Figures 5c, 5f, 5i and 5l that the mean TBB of quadrants No.4 and No.5 is smaller than that of No.1 and No.8 in the north side (except between −3 h and 1h for Saomai and prior to −13 h for Khanun). Quadrants No.3 and No.6, located beside the southern quadrants, also have mean TBB smaller than quadrants No.2 and No.7, located in the northern side. However, mean TBB is similar among quadrants No.2 and No.3 in the eastern side of Wipha and Khanun, and quadrants No.6 to No.7 in the western side of Saomai, varying alternatively in relatively small amplitudes. The cause could be two folds. The first is a small vertical wind field. For Wipha (Figure 5a), for instance, it is only 0.6 m/s within the time −6 h to 0 h. Although convection seems to occur more easily in quadrant No.3 than in quadrant No.2 for this period of time, as shown in Figure 5b, it does not happen as expected, and as a matter of fact, the quadrants are generally consistent (Figure 5c). The second cause is that convection is continuous within a particular region while the region with likely appearance of convection is only 90° in azimuth coverage and defined based on the maximum number of gridpoints where convection occurs (Figure 4). By contrast, mean values of TBB are thresholds by which the intensity of convection is determined, making the two differ to some extent. As shown in Figure 3b, the convection is more significant in the western side than in the eastern side of the TC prior to −8 h and the opposite is true after it. Comparisons of the mean TBB curves of quadrants No.2, No.3, No.6, and No.7 in Figure 5c, 5f, 5i, and 5l show that their values are basically consistent prior to −24 h, except for the slow-moving Matsa whose northern quadrants are already over land. With the elapse of time, however, the convection in the western portion weakens or maintains while maintaining or strengthening in the eastern portion of the TC, leading to changes in relative intensity of east-west convection. It is mainly caused by three reasons. First, it is affected by vertical wind shear and TC motion. Take Khanum for instance. Its vertical wind shear increases significantly in the time between −13 and −7 h, being 9.3 m/s at maximum. Corresponding to this process, the mean TBB of quadrants No.5 and No.6 is much strengthened. Second, with the same magnitude, vertical wind shear plays a more significant role in the asymmetric distribution of convection than TC motion[10, 21]. For instance, Wipha has comparable shear strength and motion velocity prior to −9 h except that the former (latter) is likely to give rise to western (eastern) convection. As shown in Figure 5c, however, the mean TBB of quadrant No.6 is even smaller than quadrant No.3. Third, the landfall process has a role to play. See the following section for detail.

4.2 *Underlying surface terrain on the coast*

Figures 5c, 5f, 5i and 5l present, with dashed and dotted lines, the time of landfall on the northern and western (or eastern) quadrants of the TC. As shown in the evolution of TBB averaged over each of the quadrants, the landfall process is one of the important factors that affect the asymmetric distribution of convection of the TC. At 5 to 8 h prior to landfall in the northern part of the TC, convection is relatively weak or weakens significantly. The related quadrants are associated with the direction to which the TC moves. As far as the coast of east China is concerned, Khanun is a TC that has the maximum mean moving direction (at 202°). Therefore, the quadrants under the effect are those in the northern to western portion of the TC, i.e., at quadrants No.7 and No.8 (Figure 5i). By contrast, Saomai has the least of moving direction (at 170°). As a result, the quadrants being affected are the northern to eastern portion of the TC, i.e., at quadrants No.8, No.1 and No.2 (Figure 5f). For Wipha whose direction of motion is between the above two TCs, it has a mean direction of 191°, making the two main northern quadrants (No. 8 and No. 1) affected (Figure 5c). Matsa varies relatively large in moving direction shifting from 226° to 184° such that No.8 and No.1 in the north are the quadrants affected, as well as No.2 (Figure 5l). In addition to the moving direction, it also has something to do with a relatively slow moving speed (Figure 5j). Small moving speeds form weak frictional convergence in the boundary layer. Furthermore, when the TC interacts with the coastal terrain in the east of China, the uplifting velocity is relatively small, making it unlikely for significant convection to form. Landfalls at the northern quadrants intrigue the fluctuation of the mean TBB in the difference of north-south convection, like the maxima around −14 h in Figure 3a. These landfalls are followed by the intensification of convection at related quadrants, which is most evident in Wipha and Saomai (Figures 5c & 5f). As shown in a numerical study by Chen et al.[21], due to land-surface friction, spiral rain bands are likely to form in the front quadrants of a landing TC and maintain for extended time. This finding is consistent with the observational results of TCs making landfall on the coast of the east of China. The whole process lasts between five and eight hours, shown as the decrease of mean TBB differences between the northern and southern quadrants at −4 h (See Figure 3a).

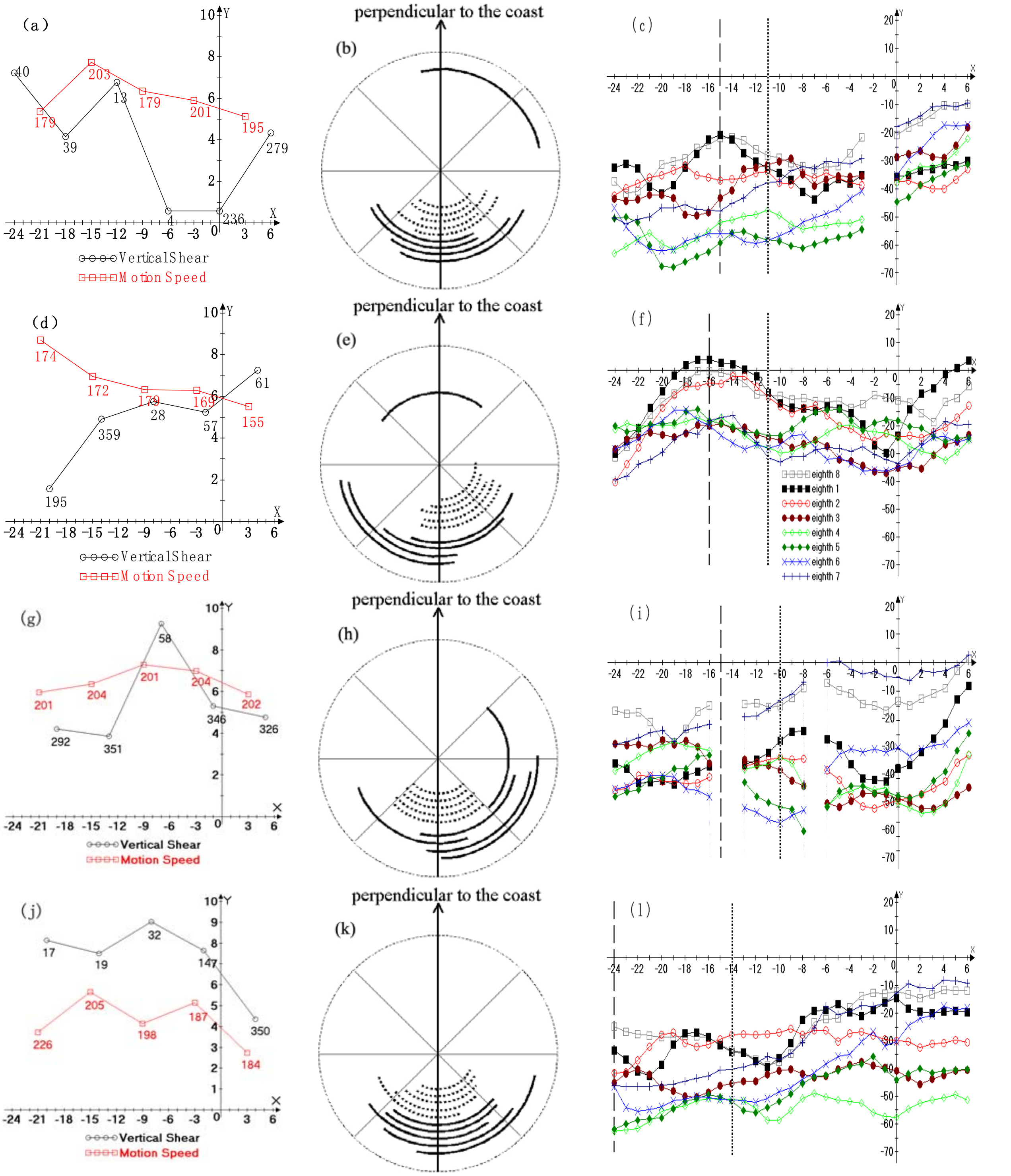


Figure 5. TCs Wipha, Saomai, Khanun, and Matsa are presented downwards. The left column is the vertical wind shear and TC moving speed is in m/s as well as the approaching direction of the TC relative to the coastline of southeast China; the middle column is for the quadrants where convection is likely to appear where the outward solid curves (inward dashed curves) are for such quadrants resulting from the shear (TC motion) that varies with time; the right column is the mean TBB for the 1/8 quadrants varying with time (units: °C), where the dashed and dotted lines are for the time of landfall at the northern and western (or eastern) quadrants.

Another significant change in convection is taking place in the landfalling of the western or eastern quadrants of TCs. Wipha, Khanun and Matsa touched land at their western quadrants first. Then, the average TBB at the western quadrants No.6 and No.7 weakened substantially while maintaining at the eastern quadrants (as in Wipha and Matsa) or strengthening (as in Khanun). By contrast, Saomai made landfall with its eastern quadrants and then convection intensified at both of its eastern and western quadrants. In fact, Saomai intensified to become a super typhoon after its northern quadrants make landfall, accompanied by a well-defined process of convective intensification (Figure 5f). If the asymmetricity of convection, instead of TC's overall intensity, is taken into account for the quadrants, variation of the east-west convection can be accounted for mainly by the process and landing angle of the landfall. As shown in a study with numerical simulation[21], it is the landfall that brings about a clear wave-1 structure in the TC through which relatively warm and humid air is cyclonically fed from the ocean into the right side of the TC track. Meanwhile, relatively dry and cold air is transported to the left side. During the landfall, the changes in the flux of latent heat from the underlying surface are therefore the main reason for the asymmetric distribution of convection between the eastern and western quadrants and the weakening of the TC. Landfalls by the eastern and western quadrants cause the mean TBB (reflecting the difference between them) to fluctuate, which is shown in Figure 3b in which the difference attains maximum at around −11 h.

5 CONCLUDING REMARKS

The TBB data of all the TC cases making landfall on the coast of East China covered by FY-2 weather satellite during 2005 to 2007 are used to study the asymmetric distribution of TC convection and its causes from the viewpoint of the vertical wind shear, TC motion and track position relative to the coast.

As shown in the study, over the 30 hours prior to and after the landfall, the convection is much asymmetric for various quadrants and always stronger in the southern quadrants than in the northern ones. For the east-west direction, it is stronger in the western quadrants than in the eastern ones when the TC is far from landing; after −8 h it becomes stronger in the eastern quadrants and the difference gets larger with time.

As shown in the statistics on the relationships between moderate-intensity vertical wind shear / TC moving speed and TC convection at a large radius (r>1°), convection is likely to take place at the downshear quadrants and at the rear quadrants. The results presented above give account of the most of the asymmetric convection in the north-south direction and part of it in the east-west direction. Some of the remaining asymmetricity results from restricted convection at quadrants related to the landfall. Besides, the relatively large-scale and high terrains in the coastal area of the east of China also give rise to or strengthen the convection due to topographical lifting at the eastern quadrants during the post-landfall time. The landfall angles relative to the coastline and coastal terrain may be the main reasons behind the asymmetric distribution of convection with TCs making landfall on the coast of the south and east parts of China.

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