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OBSERVATIONAL ANALYSIS OF ASYMMETRIC DISTRIBUTION OF CONVECTION ASSOCIATED WITH TROPICAL CYCLONES “CHANCHU” AND “PRAPIROON” MAKING LANDFALL ALONG THE SOUTH CHINA COAST

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Abstract: Observational data of mesoscale surface weather stations and weather radars of Guangdong province are employed to analyze the asymmetric distribution of convection prior to, during and after landfall for tropical cyclones of Chanchu and Prapiroon making landfall on the south China coast in 2006. The results showed that strong convection is located in the eastern and northern sectors of the landfalling Chanchu and Prapiroon, namely in the front and right portions of the TC tracks, for a period of time starting from 12 h prior to landfall to 6 h after it. Their convection also had distinct differences in the vertical direction. The analysis indicated that although the landfall of Chanchu and Prapiroon has the same asymmetric distribution of convection, the causes are not exactly the same. The asymmetric distribution of convection in the case of Chanchu is mainly correlated with the impacts of a strong environmental vertical wind shear, low-level horizontal wind shear, and low-level convergence and divergence. In the case of Prapiroon, however, the asymmetric distribution of convection is mainly associated with the impacts of low-level convergence and divergence.

Key words: asymmetric distribution of convection; tropical cyclones Chanchu and Prapiroon; observational analysis

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1 INTRODUCTION

The tropical cyclone (TC) is one of the most disastrous weather systems. Most of the damage is caused when it makes landfall. In fact, TC is the strongest weather system of torrential rain and domestic and abroad records of extreme torrential rain are mostly related to TC [1]. One of the most destructive elements of landfalling TC is the torrential rain that causes widespread flooding, and the other is the strong wind that causes storm surge and wind damage. Therefore recognizing the pattern of convective distribution associated with the landfalling TCs is a key to accurate forecast of the precipitation brought about by landfalling TCs. Many observational and numerical studies have identified much asymmetry in the convection distribution associated with landfalling TCs. Earlier studies based on raingauge data suggested that coastal rainfall was more pronounced to the right of the track in Northern Hemisphere TCs [2-4], although Miller [2] showed that the difference in rainfall between the right and left sides of the storm was insignificant. Some numerical studies also showed the maximum precipitation in the forward right quadrant of TC during and after landfall [5-6]. Dunn and Miller [7] explained this asymmetric rain distribution by postulating that differential surface friction between land and sea would induce a frictional convergence (divergence) to the right (left) of a landfalling TC in the Northern Hemisphere.

With regard to the convective distribution of

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landfalling TCs, some recent studies gave a different opinion that the convective activity was pronounced to the left of the TC track [8-12]. Powell's [13] explanation is that the frictional convergence reasoning cannot be the only determining factor of the coastal rainfall maximum; other parameters, from large-scale environmental situations to small-scale local topographic effects, have to be taken into account as well. In a recent study, Wong and Chan [14] identified asymmetries in vertical motion and diabatic heating (and hence convection and rainfall) as TCs approach the coast using a simple modeling study with different roughness lengths. The study of Lin et al. [15] indicated that the spatial distribution of rainfall was mainly quasi-symmetric on the left and right of the TC track, the right of TC track, or both the up and down sides of TC track during TC landfall in the south of China. Yi et al. [16] found that a band of strong radar echo occurred in the right-front of TC movement during landfall, and topography had a pronounced influence on the asymmetric distribution of typhoon rainfall when they analyzed the rainfall of landfalling typhoon Rananim. Some studies also showed that the altitude and slope of topography, layout of the land, and island terrain, etc. all have obvious effects on the distribution of typhoon rainfall [17-19].

The distribution of convection associated with TCs making landfall may be determined by the interaction of many factors. The asymmetric distribution of convection and its influences on TCs may be different from case to case. This study aims to analyze the asymmetric distribution of convection of two TCs, Chanchu and Prapiroon, that made landfall on the south China coast in 2006, by using the observational data of mesoscale surface weather stations and Doppler radars in Guangdong province and to discuss the causes of asymmetric distribution of convection.

2 DATA AND METHODS

2.1 *Data*

The 6-hourly best-track data of TCs are derived from the Colorado State /Tropical Prediction Center in the United States. The observational data of radar reflectivity are obtained from the Guangzhou CINRAD/SA radar (at 113.36°E, 23.00°N with 180.3 m in altitude) and Shantou CINRAD/SA radar (at 116.74°E, 23.28°N with 460.0 m in altitude), respectively. The radar data include nine non-isometric elevation angles from 0.5° to 19.5° in the vertical direction, and azimuth angles are from 1° to 360° with a resolution of 1° and a time resolution of 6 minutes. The maximum scan radius of reflectivity in the radial direction is 460 km with a resolution of 1 km. The observational data of surface mesoscale hourly precipitation are derived from 564 surface automatic weather stations and 86 conventional, basic weather stations in Guangdong, China. The vertical wind shear and horizontal wind field are obtained from the NCEP Global Final Analysis (FNL) data available four times a day on 1°×1° grids over the United States.

2.2 *Methods*

The intermediate hourly data of TC track between the standard hours are available by using a natural cubic spline fit of the 6-h best-track data. The landfall time is determined as the time when the TC first crosses the south China coastline segments from sea onto land. Radar reflectivity of each elevation angle is projected on a horizontal plane. The method adopted to calculate the vertical wind shear is similar to that of Hanley et al. [20], i.e., the symmetric vortex over the TC center at a radius of 600 km is removed by subtracting mean tangential wind at an interval of 200 km.

The method of investigating the asymmetric distribution of convection along the south China coast is essentially the same as the one used by Chan et al. [11] and Liu et al. [12], i.e., the south China coast is defined as the direction either due "east" or due "west". The circle centered on the TC center with a radius of 200 km is divided into four sectors, eastern, southern, western and northern, each of them spanning 90° of azimuth. The "eastern", "southern", "western" and "northern" descriptors are defined relative to the south China coastline. The eastern (western) sector is defined as the sector actually spanning from 27° to 117° (207° to 297°). Similarly, the southern (northern) sector is the sector actually spanning from 117° to 207° (297° to 27°) (see Fig. 1). Although the landfall site of Chanchu is slightly out of the defined south China coast, the uniform sectors are used in this study.

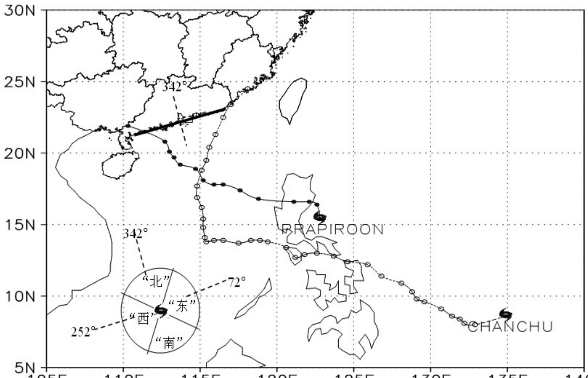


Fig.1 Best tracks of TC Chanchu (dashed line with open circles) and Prapiroon (solid line with closed circles). Typhoon symbol: location of cyclogenesis; bold solid line: the coast of south China; the domain of "eastern", "southern", "western" and "northern" sectors are relative to the coastline, and the normal

line of the South China coast (its real bearing angle is 342°) is defined as “true-north” bearing.

3 THE ASYMMETRIC DISTRIBUTION OF CONVECTION OF TCS CHANCHU AND PRAPIROON

3.1 *Brief accounts of TCs Chanchu and Prapiroon*

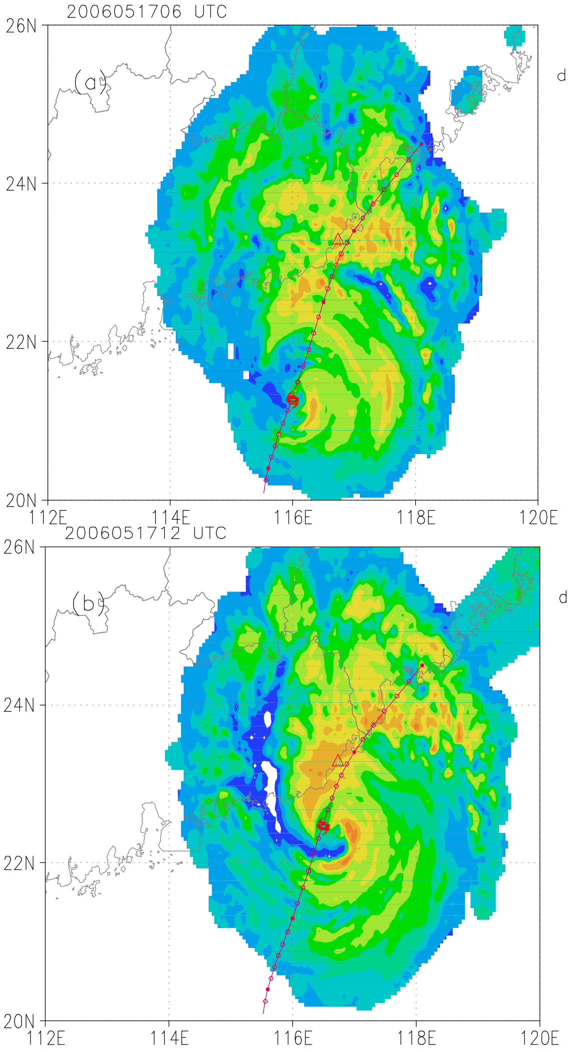
Chanchu formed over the southeast ocean off the Philippines on 8 May 2006. It moved slowly toward the west-northwest at first and then passed through the Philippines before entering the middle part of the South China Sea on 15 May and intensified gradually into a severe typhoon. Then it turned to move northward. When approaching the south China coast, it headed northeastward with its intensity decreasing. At about 1800 UTC (same below) 17 May, it made landfall near Shantou in the eastern part of Guangdong before moving along the coast and entering Fujian province. Ultimately, it weakened and disappeared over the sea (Fig. 1).

Prapiroon formed over the Philippine Sea around 31 July 2006. It kept moving to the northwest for some time before entering the South China Sea after crossing the Philippines with its intensity continuing to increase, and developed to become a typhoon on 2 August. At about 1200 August 3, it made landfall near Yangjiang in the western Guangdong province, and then moved into Guangxi Autonomous Region and disappeared after weakening to a low pressure (Fig. 1).

3.2 *Asymmetric distribution of convection*

In this study, the observational data of reflectivity of the Shantou radar is used for Chanchu. Due to the absence of observational data of the Yangjiang radar, the reflectivity data of the Guangzhou radar is used for Prapiroon. Moreover, the change in reflectivity only up to 12 h prior to landfall through the time 6 h after it (referred to as “the time around landfall” hereafter) is analyzed because of the limited observational range of radar. Before Chanchu’s landfall, strong radar reflectivity (> 30 dBZ) mainly occurred in the eastern and northern sectors (Fig. 2a and 2b); during and after landfall, relatively strong reflectivity still existed in the eastern and northern sectors. Moreover, the range of the strong radar reflectivity decreased substantially during the landfall (Fig. 2c); both its intensity and range decreased significantly after landfall (Fig. 2d). It is shown that the post-landfall convective precipitation of Chanchu decreased remarkably with TC intensity.

For Prapiroon, due to the long distance of the Guangzhou radar from the site of landfall, the part of the convection far away from the radar may be too vague to be captured. When seen from the Guangzhou radar only, stronger reflectivity mainly occurs in the eastern and northern sectors for the time around landfall and there are even some bands of strong radar reflectivity outside the 200-km radius from the eye. The area with strong radar reflectivity is corresponding to strong convection; it is shown that Prapiroon has significant mesoscale convection (Fig. 3a-3d). Seen from the observational data of both the Shantou and Guangzhou radars, the radar reflectivity of both Chanchu and Prapiroon is much asymmetrical during landfall and strong radar reflectivity is mainly found in the eastern and northern sectors.



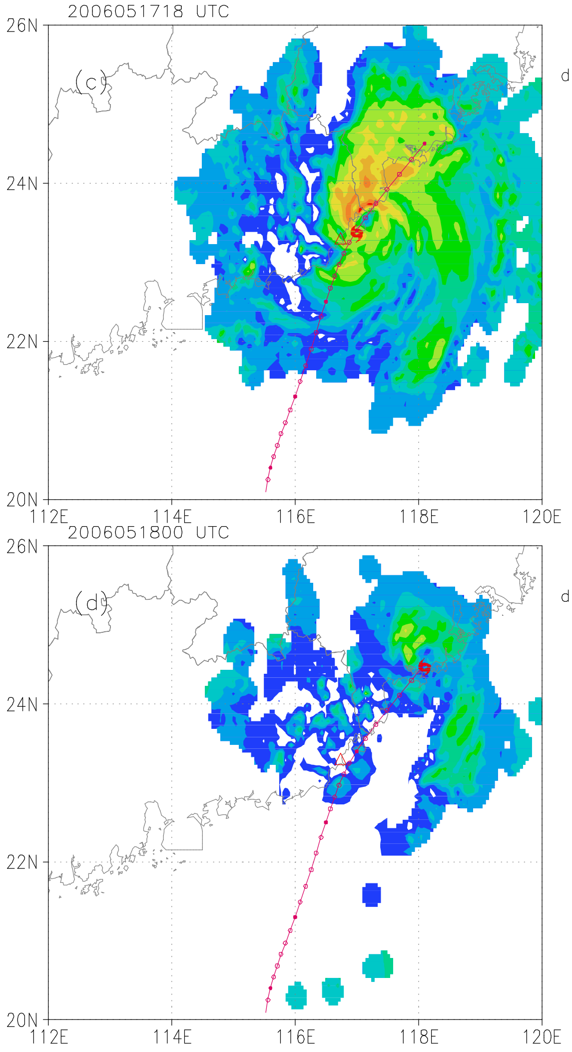
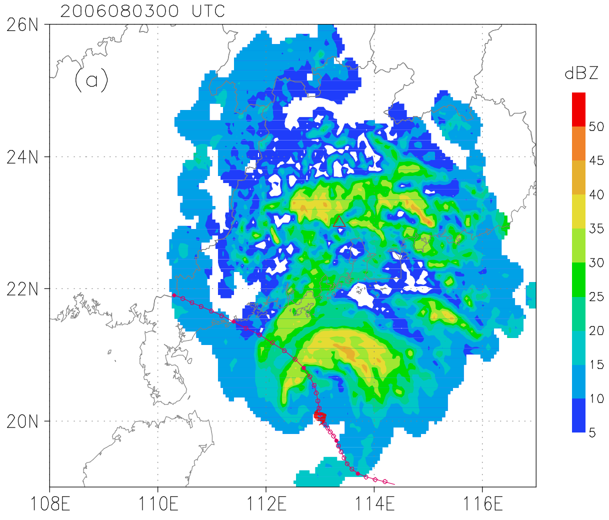


Fig.2 Hourly migration track of TC Chanchu and associated reflectivity of the Shantou radar at an elevation angle of 0.5° at 0600 May 17(a), 1200 May 17(b), 1800 May 17(c), and 0000 May 18(d). The typhoon symbol indicates the location of the eye and the open triangle indicates the location of the radar.



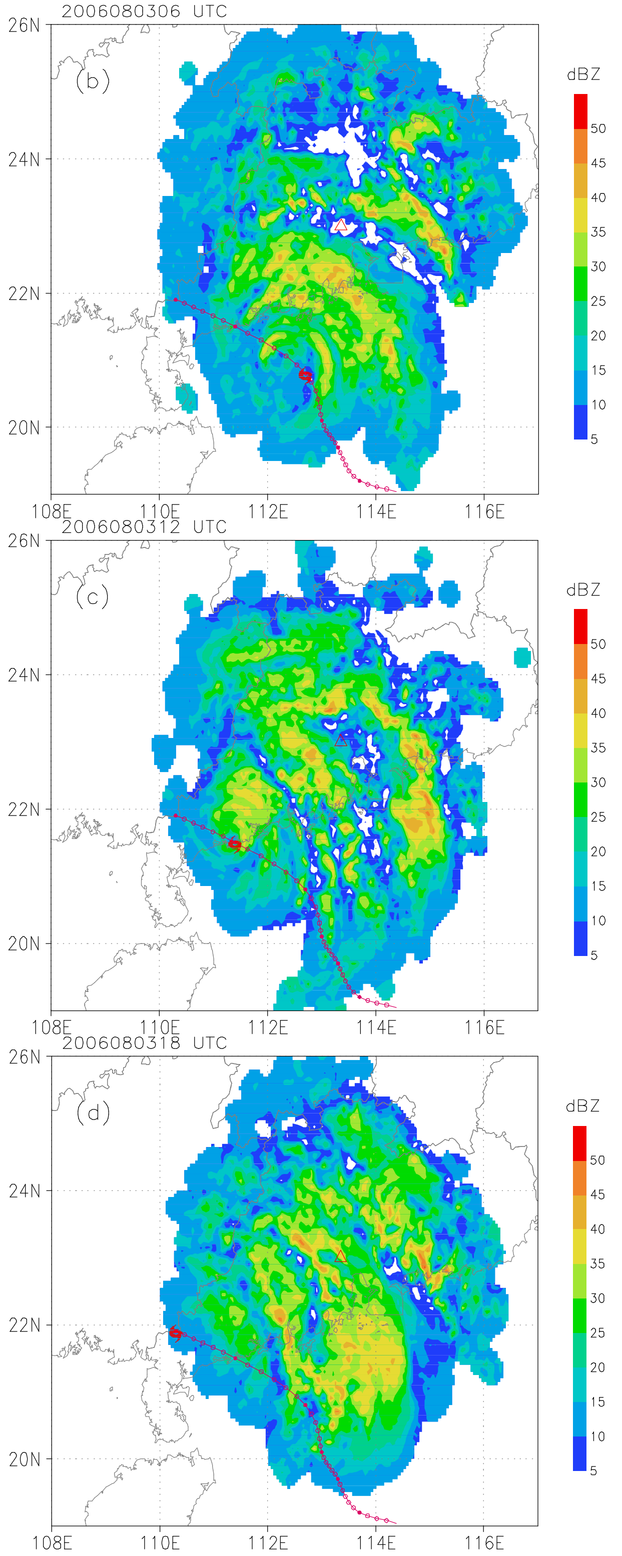
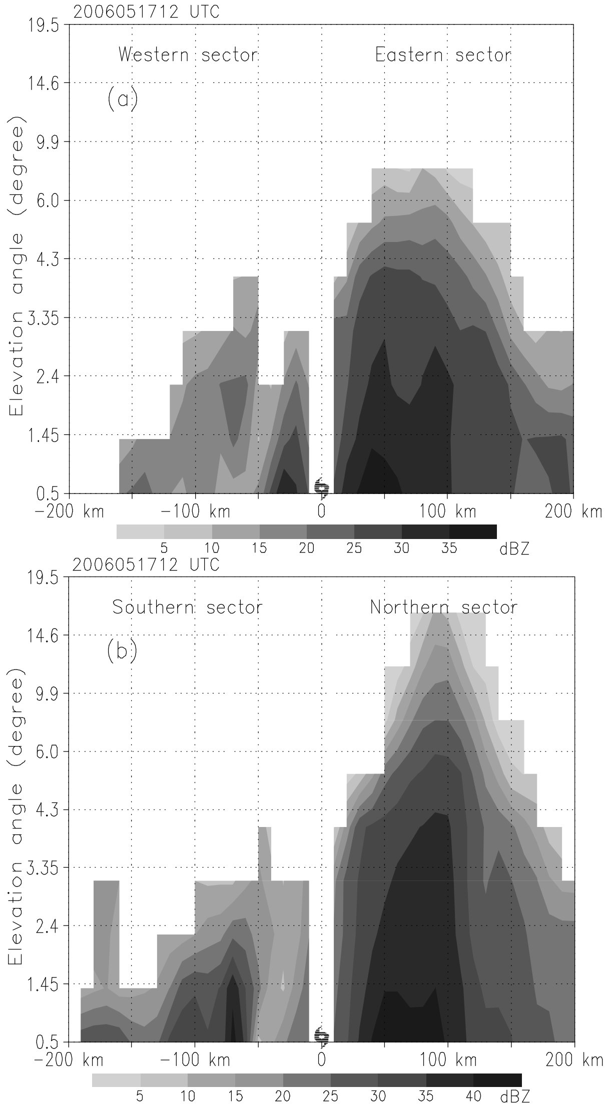


Fig.3 Same as Fig.2 but for Prapiroon and the Guangzhou radar at 0000 August 3(a), 0600 August 3(b), 1200 August 3(c), and 1800 August 3(d).

To further analyze the vertical distribution of convection associated with TC landfall, Fig. 4 gives the vertical section of radar reflectivity of Chanchu prior to and during landfall. It can be seen that the radar reflectivity is very strong and its radial range is quite large and the height of strong reflectivity is higher in the eastern (northern) sector than in the western (southern) sector of the TC core prior to landfall at 1200 UTC 17 May (Fig. 4a & 4b). In contrast, the intensity of reflectivity is strong, the radial range of strong reflectivity is very large, but the height of reflectivity is generally lower in the eastern sector than in the western sector during the landfall of Chanchu at 1800 May 17. Moreover, there is a deep mesoscale strong reflectivity in the range of 20 to 40 km west of the TC core. Shown to be in the interior of the TC, strong mesoscale convection causes heavy torrential rain when the TC makes landfall (Fig. 4c). Comparatively speaking, the intensity of reflectivity is stronger, the radial range of strong reflectivity is much larger, and the height of strong reflectivity is higher in the northern sector than in the southern sector (Fig. 4d). It can be seen that Chanchu is not only significantly asymmetrical in the horizontal direction but also much different in the vertical direction.



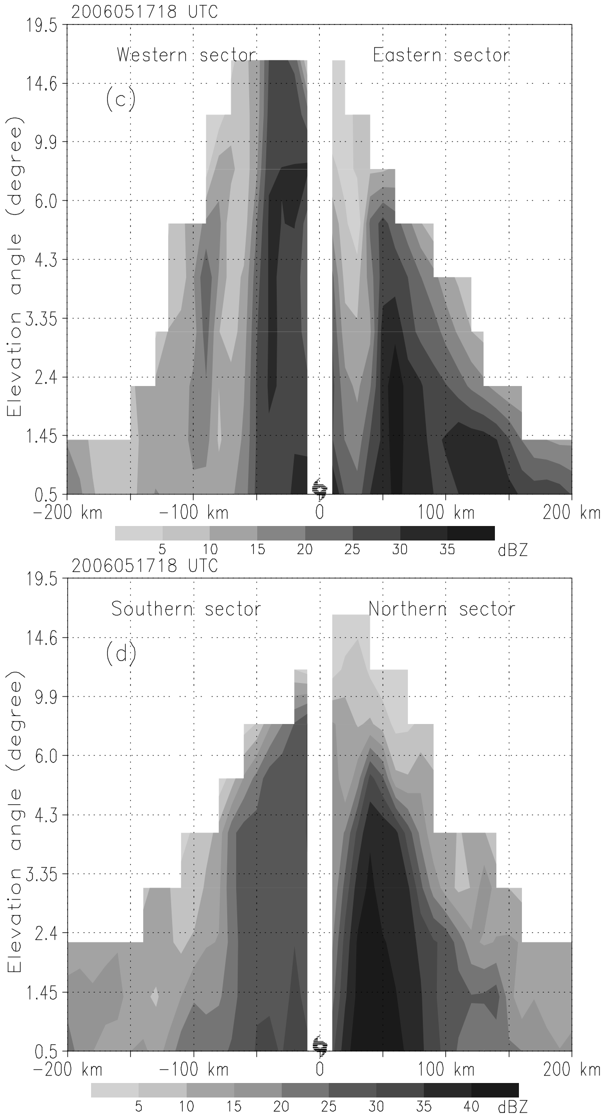
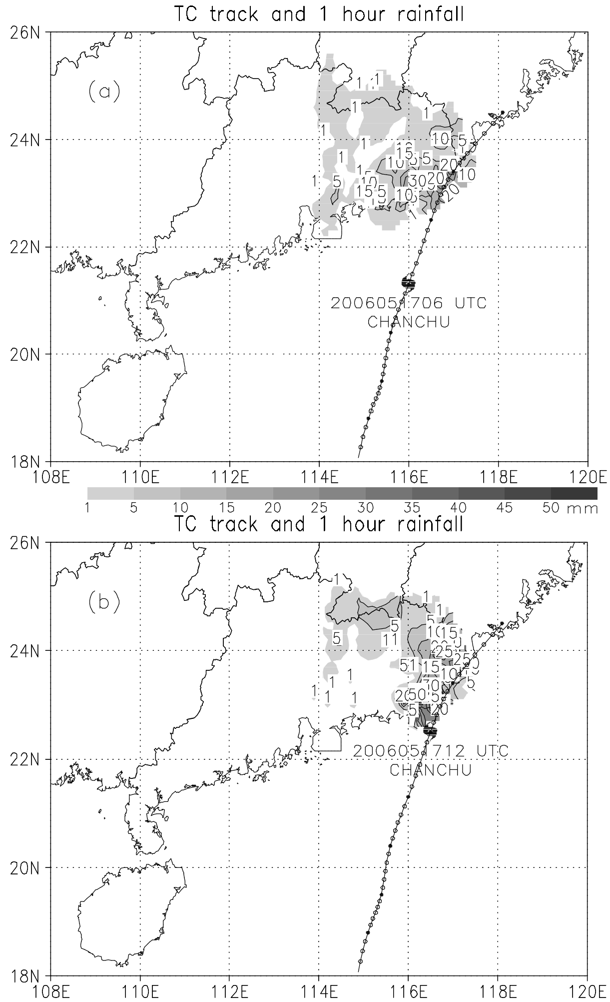


Fig.4 Vertical cross sections of reflectivity of the Shantou radar with different elevation angles across the center of Chanchu (mean value of the fan-shaped area spanning from –22.5° to 22.5° relative to the sector point of the directional true bearing) along the west-east direction at 1200 May 17(a), along the north-south direction at 1200 May 17(b), along the west-east direction at 1800 May 17(c), and along the north-south direction at 1800 May 17(d). The typhoon symbol represents the TC center. The abscissa is a radial distance from the TC center with a resolution of 10 km and the ordinate is the elevation angle of radar.

To further identify the asymmetric distribution of convection in landfalling TCs, Fig. 5 gives the hourly TC migrating track and distribution of hourly precipitation from surface weather stations over Guangdong prior to and after Chanchu's landfall. It is known from the figure that very strong precipitation always exists in the east of the province during this time. Strong convection is shown to be in the northern sector of the TC core. The precipitation in the east of Guangdong decreased significantly after landfall and the distribution of hourly precipitation at surface stations is consistent with that of radar reflectivity (Fig. 2). The convection is weak in the western sector and further verifies the result of radar reflectivity analysis.

Figure 6 gives the hourly TC migrating track and the distribution of hourly precipitation of surface weather stations over Guangdong prior to and after the landfall of Prapiroon. It is noted that strong peripheral precipitation of TC occurred near the Pearl River estuary near the central Guangdong prior to landfall and strong convection was present in the north of TC center. During and after the landfall, several bands of strong precipitation occurred in the central and eastern parts of the province and the spatial distribution of precipitation is consistent with that of radar reflectivity (Fig. 3) and strong convection occurred in the east of TC center. Moreover, the aforementioned feature of TC convective distribution obtained from the analysis by using the data of radar reflectivity is locally verified by the spatial distribution of hourly precipitation of surface stations.



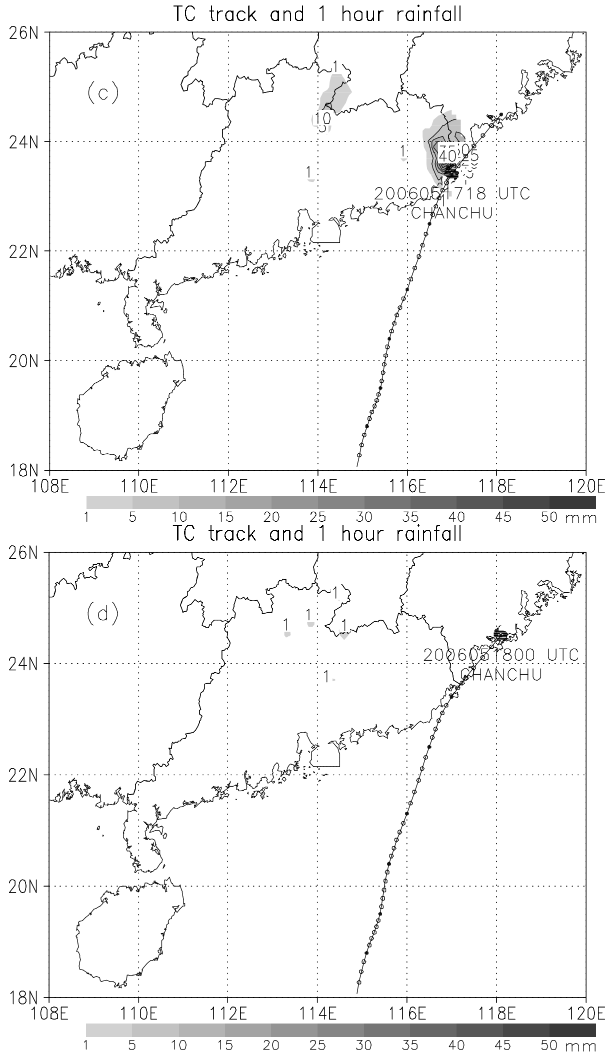
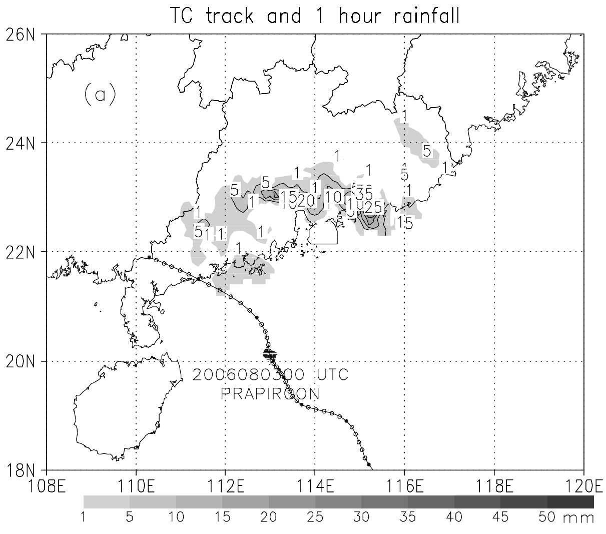


Fig.5 Hourly migrating track of Chanchu and the distribution of hourly rainfall of surface weather stations over the region of Guangdong province at 0600 May 17(a), 1200 May 17(b), 1800 May 17(c), 0000 May 18(d). The typhoon symbol indicates the location of the TC center.



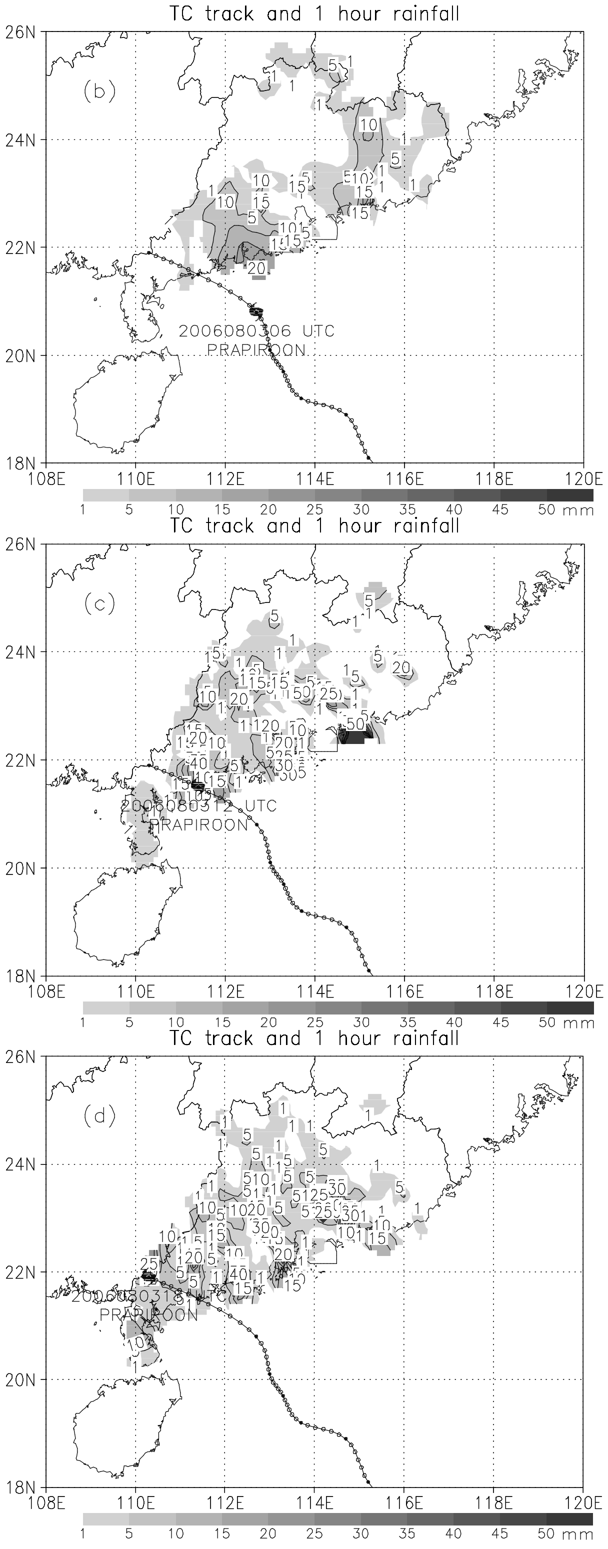


Fig.6 As in Fig.5 but for TC Prapiroon at 0000 August 3(a), 0600 August 3(b), 1200 August 3(c), 1800 August 3(d).

To further compare the temporal change in the intensity of TC convection between the eastern and western sector, this paper calculates the mean value of radar reflectivity in the fan-shaped area spanning from –22.5° to 22.5° relative to the directions of due east and due west for the time around landfall with 1-h intervals. Figure 7 gives the changes in the mean radar reflectivity of Chanchu and Prapiroon in the eastern and western sectors covering the time. It is known that this is the time when the reflectivity of Chanchu is significantly stronger in the eastern sector of the TC center than in the western one and so is the convection (Fig. 7a). Similarly, the convection of Prapiroon is much stronger in the eastern sector of the TC center than in the western one in this period (Fig. 7b); the reflectivity in the western sector is very small 6 h after landfall, which may be attributed to the distant location of the radar. Of course, owing to the location of the Guangzhou radar, which is far away from the landfall site of Prapiroon, the analytical result of the magnitude of radar reflectivity in different sectors may vary, but the situation of the above convective asymmetric distribution will not change basically.

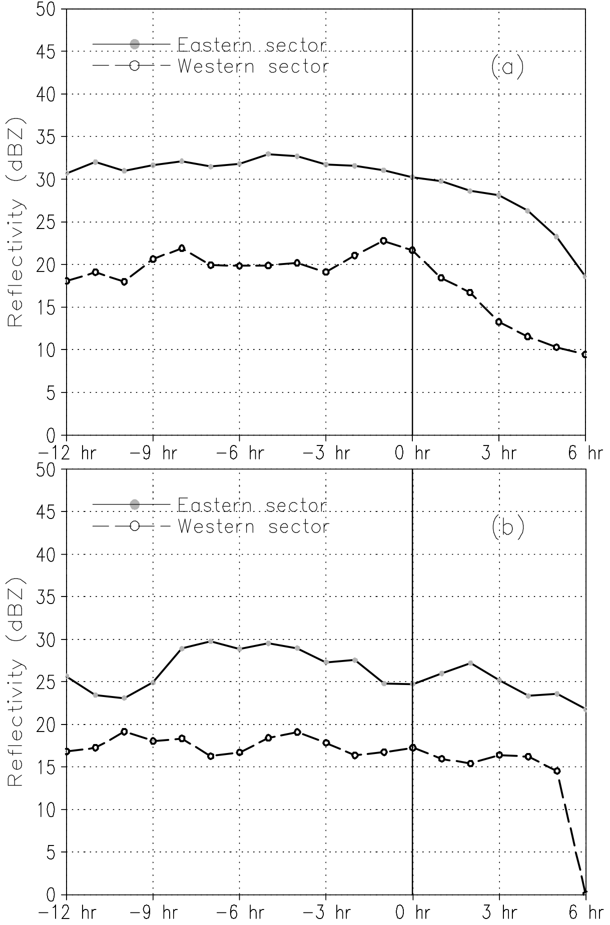


Fig.7 Mean reflectivity of radar in the eastern and western sectors changing with time (unit: h) for Chanchu (a) and Prapiroon (b). The abscissa is relative to the landfall time and the thick, vertical line at the 0-h mark indicates the landfall time. Negative values represent the time before landfall and positive values that after landfall.

Many observational and numerical studies have suggested that vertical wind shear is one of the significant factors that affect the distribution of TC convection and strong convection is favored to occur on the left side of a vertical shear vector or on the downshear quadrant [11, 12, 21-24]. As far as the case of Chanchu is concerned, the mean vertical environmental wind shear in the range of a 500-km radius around the TC center is up to 10 m s^{-1} during the landfall (Fig. 8a). According to the previous results, strong convection is favored to occur in the left or front part of the vertical shear vector, leading to the possibility that strong convection of Chanchu in the eastern and northern sectors may be partly associated with the strong vertical wind shear. In the case of Prapiroon, however, the mean vertical environmental wind shear in the range of a 500-km radius around the TC center is relatively weak during landfall (< 5 m s^{-1}) and the impact of the vertical wind shear on the distribution of Prapiroon's convection is not significant (Fig. 8b).

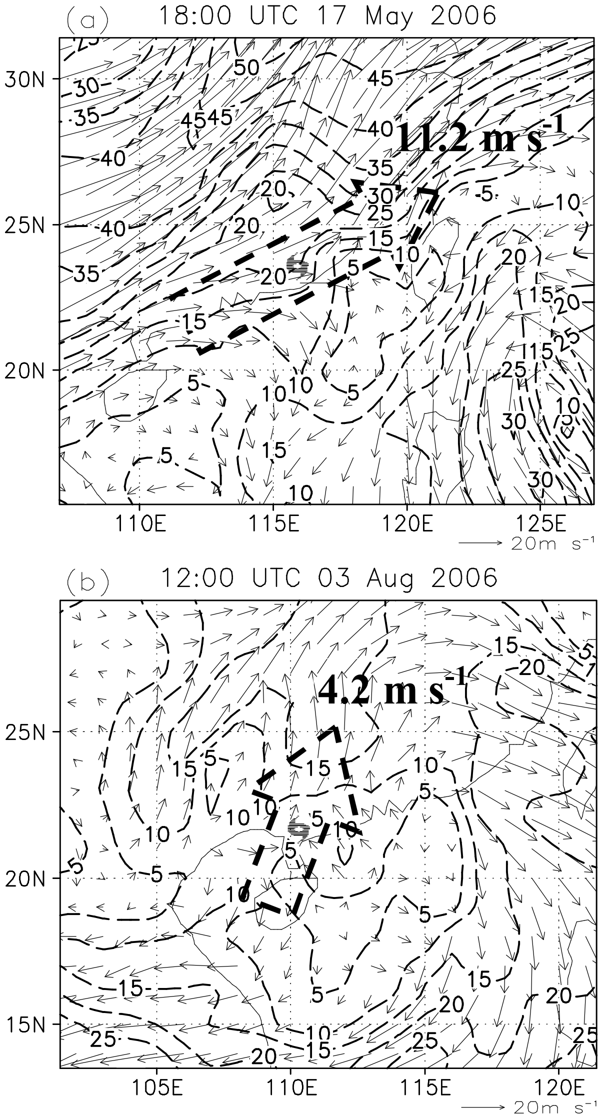
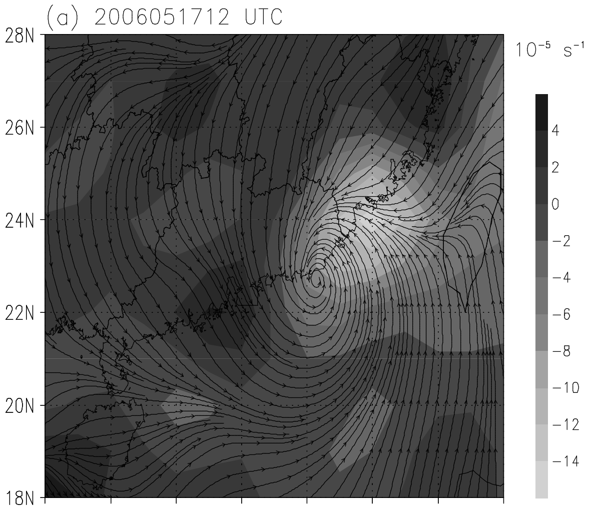


Fig.8 The 200-hPa to 850-hPa vertical environmental wind shear at 1800 May 17 for Chanchu (a) and 1200 August 3 for Prapiroon (b). The thin, dashed lines are for the magnitude of the wind shear (m s^{-1}). The typhoon symbol indicates the location of the TC center at the time. The large, thick arrow indicates the mean environmental wind shear in the range of a 500-km radius around the TC center, and the numeral before the arrow represents the magnitude

Additionally, low-level horizontal wind shear, convergence and divergence also can have important influence on the asymmetric distribution of the convection. From a stream field and divergence field at 1000 hPa, it is seen that a very obvious horizontal wind shear and a strong convergence area appear 6 h before landfall in the eastern and northern sectors of the Chanchu's center and last until landfall; this kind of distribution is basically consistent with that of Chanchu's strong convection in these sectors (Fig. 9). The low-level horizontal wind shears around the TC center are not distinct during this period for Prapiroon, and there is a low-level convergence area around the TC center in the eastern and northern sectors; this kind of distribution of strong convergence area is basically consistent with that of the strong convection (Fig. 10). It is known that the asymmetric distribution of convection of Chanchu is associated not only with the impact of vertical wind shear of the environment but also the low-level horizontal wind shear, low-level convergence and divergence; but for Prapiroon, it is mainly associated with the impact of low-level convergence and divergence.



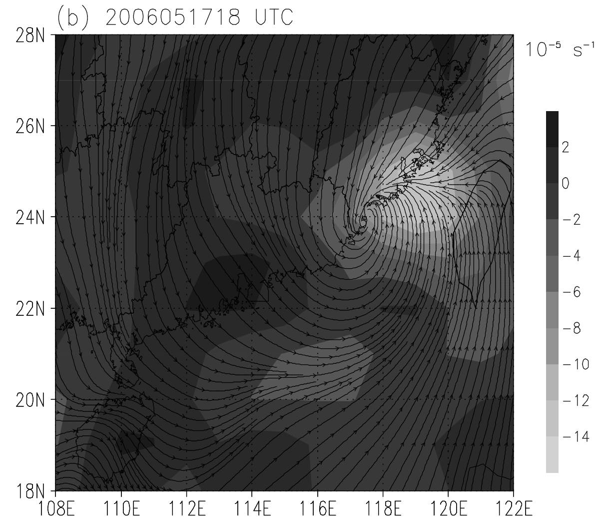


Fig.9 The distributions of stream field and divergence of Chanchu at 1000 hPa, where positive values of the shadow are corresponding to divergence and negative values to convergence at 1200 May 17(a) and 1800 May 17(b).

4 CONCLUSIONS AND DISCUSSION

In this study, the observational data of hourly precipitation of mesoscale surface automatic weather stations and reflectivity of weather radars over the region of Guangdong province are employed, and the asymmetric distributions of convection for TCs Chanchu and Prapiroon prior to, during and after landfall on the south China coast in 2006 were analyzed. The results show that the strong convection of Chanchu and Prapiroon mainly locates in the eastern and northern sectors of the TC centers for the time 12 h prior to landfall through the point 6 h after it, i.e., on the right side and in the front of TC migrating tracks; the distribution of convection of the landfalling TCs shows not only significant horizontal asymmetry but also substantial difference in the vertical direction. Further analysis reveals that the distribution of asymmetric convection of landfalling Chanchu is associated with the impacts of strong vertical wind shear of the environment, low-level horizontal wind shear, and low-level convergence and divergence. For the case of TC Prapiroon, however, the vertical wind shear of the environment is relatively weak, and no obvious low-level horizontal wind shear exists near the TC center; the distribution of asymmetric convection is mainly associated with the impacts of low-level convergence and divergence.

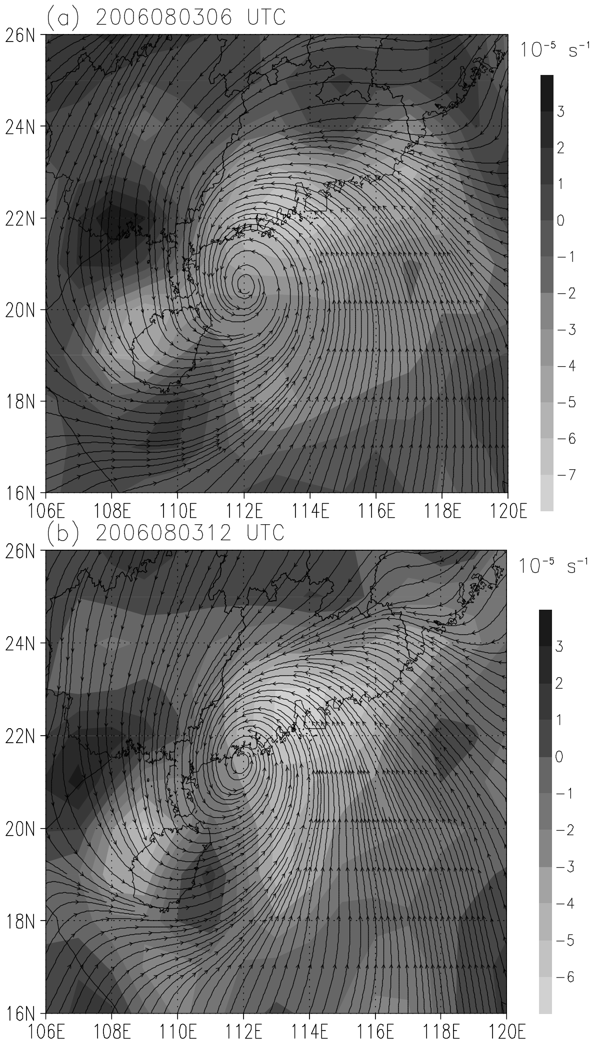


Fig.10 As in Fig.9 but for TC Prapiroon at 0600 August 3(a) and 1200 August 3(b).

In view of the limited data range of the radar and surface weather stations, the analysis of the distribution of asymmetric convection may be subject to certain influence during the landfall of Prapiroon, though it has no obvious influence on the conclusion in this study. It is known that although the strong convection of both Chanchu and Prapiroon locates in the eastern and northern sectors, their impact factors are not identical. Because the distribution of TC convection may be subject to the mutual impacts of many different factors, the distribution of convection for specific TC cases may need specific analysis.

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