RADAR OBSERVATION OF PRECIPITATION ASYMMETRIES IN TROPICAL CYCLONES MAKING LANDFALL ON EAST CHINA COAST

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ABSTRACT

This study explores, for the first time, the asymmetric distribution of precipitation in tropical cyclones (TCs) making landfall along east China coast using reflectivity data collected from coastal Doppler radars at mainland China and Taiwan. Six TCs (Saomai, Khanun, Wipha, Matsa, Rananim and Krosa) from 2004 to 2007 are examined. The temporal and spatial evolution of these TCs’ inner and outer core asymmetric precipitation patterns before and after landfall is investigated. The radius of inner-core region is a function of the size of a TC apart from a fixed radius (100 km) adopted in previous studies.

All six TCs possessed distinct asymmetric precipitation patterns between the inner- and outer-core regions. The amplitude of asymmetry decreases with the increasing TC intensity and it displays an ascending (descending) trend in the inner (outer) core. In the inner-core region, the heavy rainfall with reflectivity factor above 40 dBZ tends to locate at the downshear side before landfall. Four cases have precipitation maxima on the downshear left side, in agreement with previous studies. As TCs approaching land (~ 2 hr before landfall), their precipitation maxima generally shift to the front quadrant of the motion partly due to the interaction of TC with the land surface. In the outer-core region, the precipitation maxima occur in the front quadrant of the motion in five of the six cases before landfall. After landfall, the precipitation maxima shift from the right-front quadrant clockwise to the right-rear quadrant of the motion collocated well with the mountainous areas along the coast, which indicates the impact of topography forcing on the precipitation distribution. This study illustrated how the precipitation asymmetry in the inner- and outer-core at different stages of TC landfall is affected by storm motion, vertical wind shear and topography.

Keywords: landfalling tropical cyclone, asymmetric precipitation distribution, East China

1. Introduction

Understanding precipitation structure and its evolution in landfalling TCs is critical for improving quantitative precipitation estimate (QPE) and forecast (QPF). As TCs approaching the coastline, their precipitation distribution often becomes highly asymmetric due to increasing surface friction and reduced sensible and latent heat fluxes over land. Many researchers have investigated possible physical mechanisms that may affect the precipitation distributions in landfalling TCs using observations and numerical simulations.

Earlier observational studies based on rain gauges and coastal conventional radar observations (e.g., Koteswaram and Gaspar 1956; Miller 1964; Powell 1987; Burpee and Black 1989) showed that the coastal precipitation usually concentrated on the right of the track in Northern Hemisphere TCs during and after landfall. As proposed by Dunn and Miller (1960), such an asymmetric precipitation structure can be induced by differential surface friction between land and ocean. Other studies show that rainfall asymmetry within TCs over the open ocean are primarily affected by storm motion and vertical wind shear. For example, Parrish et al. (1982) and Blackwell (2000) have found the precipitation maximum occurred to the left of the storm track. Using data from the coastal National Lightning Detection...
Network (NLDN), Corbiero and Molinari (2002; 2003) found lightning flashes (used as a proxy of strong precipitation) often occurred on the down shear left side of TCs, indicating the impact of vertical shear on the distribution of convection within TCs. Rodgers et al. (1994) showed a precipitation maximum to the front of storm motion in a North Atlantic TC composite of satellite observations, and the location of the maximum shifted to the front-right as the storm translational speed increased.

Using satellite and coastal radar data to examine the distribution of convection in landfalling TCs along the South China coast, Chan et al. (2004) and Liu et al. (2007) found convection to be generally forced to the west of TCs near landfall for the majority of cases, which may be related to the combined effect of land interaction, storm motion and vertical wind shear. Besides the asymmetric friction caused by storm motion and the forcing of vertical shear, topography is another important factor that contributes to the precipitation asymmetry in landfalling TCs. For instance, Zhu et al. (2010) used satellite data to show that the interaction between TC circulation and the coastal complex terrain along the East China coast can significantly enhance the precipitation. Using observations from two ground-based Doppler radars, Yu and Cheng (2008) presented a detailed description of the orographic precipitation and its relationship with orographic geometry, strong upstream oncoming flow, and the precipitation inherently associated with typhoon circulation in Typhoon Xangsane (2000). Smith and Schafer (2009) found that the heavy rainfall was doubled by orographic enhancement in Hurricane Dean (2007) which finally caused severe landslide in the West Indies.

Possible mechanisms affecting the asymmetric structure of precipitation in landfalling TCs have been investigated in numerical studies. Simulations performed on the f-plane by Tuleya and Kurihara (1978) and Chan and Liang (2003) showed that surface heat/moisture fluxes are the dominant factors controlling the convection asymmetry. The precipitation maximum appeared to be located in the front and the left-front prior to TC landfall, and then shifted to the front and the right side if moisture was cut off (Chan et al. 2003). Shapiro (1983) studied the impact of storm motion on the TC asymmetry and found the maximum convergence located in the front (the right) of a slow-moving (fast-moving) translating vortex due to asymmetric friction in the boundary layer. A recent numerical study based on a β-plane simulation by Szeto and Chan (2010) showed the enhanced precipitation on the left of TCs near landfall is partly related to the effect of the β-gyres. Comparing with other factors, the impact of topography on the precipitation is a complicated issue. Lin et al. (2001) suggested that topographic rainfall could be affected by a combination of common ingredients such as steep topography, an unstable, high moisture upstream airflow, and favorable mountain geometry. Severe flooding resulting from topographic induced torrential precipitation within landfalling TCs were captured well by the numerical simulations (e.g., Gao et al. 2009; Li et al. 2003).

China is one of the countries suffering the most from landfalling tropical cyclone damage. According to the Yearbook of TCs from Chinese Meteorological Administration (CMA), the TC landfall locations in China can be divided into three types: East China coast, Taiwan Strait and South China coast. Previous observational studies based on Doppler radar and satellite data have mostly investigated the precipitation asymmetry in South China coast (Chan et al. 2004; K. S. Liu et al. 2007; Yuan and Zhou et al., 2010), but it was seldom examined in East China coast (Zhu et al. 2010; Gao and Meng 2009). In contrast to the relatively flat coastal region along the South China coast, East China coast is characterized by complex terrain. Therefore, precipitation distribution in TCs making landfall in these two regions may be different. With the deployment of the Chinese next-generation Weather Surveillance Radar 1998 Doppler (CINRAD WSR-98D) network in recent years, six TCs (Saomai, Khanun, Wipha, Matsa, Rananim and Krosa) that made landfall in East China were captured. Table 1 lists their landfall time, intensity, and mean translation speed and directions. This study explores for the first time the precipitation asymmetric structure associated with landfalling TCs in East China coast using data from these high-resolution coastal radars. Data and analysis methodology used in this study are described in section 2. The precipitation asymmetry within these TCs will be shown in section 3. Possible factors that affect the precipitation asymmetry

**Table 1.** Basic information of each TC

<table>
<thead>
<tr>
<th>No.</th>
<th>Typhoon Name</th>
<th>Landfall Time (Month/Date/Year)</th>
<th>Intensity (hPa/m/s)</th>
<th>Mean translational speed (m/s)</th>
<th>Translational Direction (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0414</td>
<td>Ranim</td>
<td>8/12/12</td>
<td>950/45</td>
<td>6.8</td>
<td>308.7</td>
</tr>
<tr>
<td>0509</td>
<td>Matsa</td>
<td>8/5/19</td>
<td>950/45</td>
<td>6.8</td>
<td>320.8</td>
</tr>
<tr>
<td>0515</td>
<td>Khanun</td>
<td>9/11/06</td>
<td>945/50</td>
<td>6.6</td>
<td>326.4</td>
</tr>
<tr>
<td>0608</td>
<td>Saomai</td>
<td>8/10/09</td>
<td>919/60</td>
<td>7.2</td>
<td>293.5</td>
</tr>
<tr>
<td>0713</td>
<td>Wipha</td>
<td>9/18/18</td>
<td>950/45</td>
<td>6.0</td>
<td>303.3</td>
</tr>
<tr>
<td>0716</td>
<td>Krosa</td>
<td>10/7/07</td>
<td>975/33</td>
<td>4.5</td>
<td>325.5</td>
</tr>
</tbody>
</table>
in landfalling TCs are discussed in section 4. Summary and conclusions are given in section 5.

2. Data and methodology

a. Data

1) Best track

The TC tracks (00, 06, 12, 18 UTC) were derived from the best track dataset compiled by CMA Shanghai Typhoon Institute (STI). When the six-minute radar data were available, the TC centers were deduced using a method called Tropical Cyclone Eye Tracking (TCET) proposed by Chang et al. (2009). This method is based on the feature that the eye region of TC is mainly occupied by weak downdraft with little convection that appears as a hole of low reflectivity in radar echo surrounded by the eyewall with high reflectivity. A disadvantage of this method is that the weak echo region of eye is usually filled by precipitation after TC landfall, which makes center tracking impossible in this period. So a linear interpolation of the last explicit TCET center and best track data is employed to get continuous TC positions. The tracks of each TC determined by the combination of the two methods are shown in Figure 1. All TC samples selected in this study were heading northwest during the analysis period.

2) Vertical shear

The Japan Meteorological Agency (JMA) Regional Spectral Model (RSM) reanalysis data which covers the East Asia with a temporal resolution of 6 h (00, 06, 12, 18 UTC) and a spatial resolution of 20 km, are used to illustrate the environmental conditions of each TC sample and to derive the environmental vertical wind shear over storm following the method of Hanley et al. (2001). The mean winds of each annular region of 100 km width from the TC center to 500 km radius are calculated and then averaged (area weighted) to obtain the environmental mean wind of the TC at each level. The environmental vertical wind shear over each storm is defined as the difference of the mean winds between 200 hPa and 850 hPa.

3) Radar data

In this paper, radar data from two coastal Doppler radars, including one CINRAD WSR-98D, located at Wenzhou (WZ) along the east coast of mainland China and one WSR-88D, located at Wu Fen Shan (WF) on the northern Taiwan, are used (Fig. 1). Both radars operated in the same WSR-88D volume coverage pattern 21 (VCP21), consisting of 9 elevations between 0.5° and 19.5° (Crum et al. 1993). The maximum reflectivity ranges for WSR-98D and WSR-
88D are both 460 km. The data quality control procedures developed by Zhang et al. (2004) is first applied to automatically remove/correct erroneous observations, including ground clutter removal. These data are then examined and edited manually using the National Center for Atmospheric Research “SOLO” software (Oye et al. 1995). After that, the quality controlled data from each radar are interpolated onto 2 km height in Cartesian coordinates. Finally, data are bilinearly interpolated onto a polar coordinate centered at the TC center for the precipitation analysis. The analysis domain extends from the TC center to 300 km radius. Grid spacing is 1 km in the radial directions, and 1 degree in the azimuthal direction. In consideration of the integrity of TC observed by radars, the analysis time is confined between 8 h before and 6 h after landfall.

b. Methodology
In previous studies, the inner-core region of TC is often defined as the area enclosed by a fixed-size circle from the TC center. For example, Corbosiero and Molinari (2003) took the radius of 100 km as the boundary of inner core. However, since the size of the inner-core region is closely related to the size of each TC (for example, the outer boundary of the primary rainband), using a fixed radius is inadequate to reveal the true characteristic for a spectrum of TCs with different sizes. Therefore, a size dependent approach is adopted to identify the radius of inner-core region for each TC in this study. Willoughby et al. (1984) put forward a conceptual model of TC structure, called Stationary Band Complex (SBC), in which the TC inner-core region is defined as the outer edge of primary rainband (their Fig. 1). Fig. 2 illustrates inner-core regions of two TCs in consideration with different sizes and the ranges are listed in Table 2.

In order to illustrate the temporal and spatial variations of precipitation distributions, we take a coordinate similar to that used in Marks (1985), which divided TC into four quadrants relative to a specified direction. In this study, storm motion or downshear direction is assigned as “North”. Under this coordinate, the four quadrants correspond to the right front, left front, left rear and right rear of motion or shear; respectively. We keep all 90 points of data in each quadrant instead of calculating the quadrant-average (as in Marks 1985) to reveal more detailed azimuthal variation of precipitation in a time-azimuth chart relative to the landfall.

3. Rainfall asymmetry
The amplitudes of wavenumber 1 (WN1) and total precipitation asymmetry\(^1\) (TPA) are analyzed through a Fourier decomposition. The observed reflectivities in an annulus can be represented as (Boyd 2001):

\[
R(\theta) = a_0 + \sum_{n=1}^{\infty} (a_n \cos(n\theta) + b_n \sin(n\theta))
\]

where \(\theta\) is the phase angle of the observation relative to the storm motion.

\(^1\)Represented by the sum of WN1 and WN2 since rainfall components at higher order wavenumbers are relatively small and could be ignored comparing with lower order wavenumbers.
true north (positive clockwise) and n the wave number. \(a_n\) and \(b_n\) are Fourier coefficients that can be used to obtain power of each wavenumber.

The percentages of WN1 and TPA relative to the axisymmetric component in the inner-core and outer-core regions are shown in Figs 3 and 4. In the inner-core region, WN1 and TPA are less than 0.4 and 0.6, indicating that TC rainfall is dominated by axisymmetric component in this region and the WN1 component accounts for the majority of the TPA. As the TCs approaching land, the precipitation asymmetries started to decrease gradually and reached a minimum about 1-3 hours after landfall, that is to say, the rainfall in TC's inner core became more axisymmetric. The amplitude of asymmetric rainfall strengthened again after that. The rainfall asymmetry in the outer core showed a similar trend with the minimum occurred ~4-0 hours before landfall compared with their inner core counterpart. The amplitude of asymmetry was overall higher in the outer core than that of the inner core. Among all the TC cases in study, rainfall of Saomai was mostly axisymmetric with less than 10% of asymmetric component. The precipitation asymmetries of the remaining storms were dominated by WN1 component with periods of enhanced WN2 asymmetry. In general, the outer core had stronger WN2 components than those in the inner core.

According to previous investigations, the amplitude of TC precipitation asymmetry is inversely proportional to its intensity (Lonfat et al. 2004). In this study, we examined the storm intensity vs. rainfall asymmetry before (stage 1) and after (stage 2) landfall. Then six TCs were sorted by storm intensity (defined as minimum sea level pressure, MSLP) in stage 1. From strong to weak, the order is Saomai, Khanun, Wipha, Matsa, Rananim and Krosa. The mean percentage of asymmetry relative to axisymmetric component is listed in Table 3. Super typhoon Saomai had the smallest precipitation asymmetry before landfall while Krosa with the highest MSLP also possessed the largest asymmetry. Except for Typhoon Matsa, the percentages of WN1 component and total asymmetry both have an increasing trend as the TC weakened, consistent with previous studies. The ascending trend of total asymmetry with declining TC intensity is illustrated in Fig 5. The comparison of mean amplitudes of precipitation asymmetry between Stage 1 (8 h before to landfall, red squares) and Stage 2 (landfall to 6 h after, green triangle) showed again the decreasing trend in the inner-core region and increasing trend in the outer-core region (Fig. 5).

4. Factors affecting rainfall asymmetry

a. Influence of vertical wind shear

Environmental vertical wind shear is a well-known factor
Table 3. Amplitude of precipitation asymmetries relative to axisymmetric component (in percentage) of innercore (before slash) and outercore (after slash) regions.

<table>
<thead>
<tr>
<th>MSLP (hPa)</th>
<th>Wavenumber 1</th>
<th>Total Asymmetries</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-8~6 h</td>
<td>Stage 1</td>
</tr>
<tr>
<td>Saomai</td>
<td>920</td>
<td>5/11</td>
</tr>
<tr>
<td>Khanun</td>
<td>945</td>
<td>13/25</td>
</tr>
<tr>
<td>Wipha</td>
<td>945</td>
<td>14/26</td>
</tr>
<tr>
<td>Matsa</td>
<td>950</td>
<td>9/35</td>
</tr>
<tr>
<td>Rananim</td>
<td>950</td>
<td>17/19</td>
</tr>
<tr>
<td>Krosa</td>
<td>970</td>
<td>21/27</td>
</tr>
</tbody>
</table>

Stage 1: 8 h before landfall to landing time;
Stage 2: landing time to 6 h after landfall

Fig. 4. As in Fig. 3 except for the outercore region.

that has a significant influence on TC precipitation distribution. Corbosiero and Molinari (2002) found a slight preference of convection on downshear left in the inner core and a strong preference on downshear right in the outer rainbands using flash distribution data. Chen et al. (2006) pointed out that the vertical wind shear was a dominant factor for rainfall asymmetry when it is >5 m s⁻¹, otherwise the effect of shear would be comparable to that of storm motion in the outer rainband region. In this study, Matsa, Khanun, and Saomai were cases with the magnitude of vertical wind shear> 5 m/s while other cases experienced weaker vertical wind shear.

In the inner-core region (Fig 6), strong convection occurred to the downshear left direction in Rananim, Khanun and Saomai before landfall. In Wipha and Krosa which were under a weak shear, intense echoes appeared on the downshear side with a preference to the right before landfall. In the outer-core region (Fig 7), the position and evolution of strong convection in each TC were quite different from one another. For Rananim, heavy rainfall was on the upshear side before landfall and shifted to downshear left after landfall. Strong convection was maintained to the downshear right of Matsa during the whole period while it was concentrated to the downshear left in Khanun and Saomai before landfall and then shifted into opposite quadrants. The location of precipitation maxima rotated from
Fig. 5. The amplitude of TC precipitation asymmetries relative to axisymmetric component (%), as a function of TC intensity (in hPa) in a) inner core and b) outer core region. Stage 1 refers to 8 hours before landfall and stage 2 means from landfall to 6 hours after.

Fig. 6. Time-Azimuth plots of radial averaged radar echo in the innercore region. The arrows point to the direction of vertical wind shear and the solid lines indicate the TC landfall time. The blue lines indicate the shear intensity (in m/s).
upshear left to downshear with a small scale active convection presented itself on the downshear or downshear right side in Wipha. This secondary maximum intense echo also appeared in the outer core region of Krosa and Khanun.

A Fourier decomposition was applied to the composite radar reflectivity in two time periods of each TC. Considering the size differences among cases, the radial radar reflectivity profile was normalized by the radius of the inner core (Fig 8). After the normalization, the ranges from 0 to 100 (100 to 200) represent the inner (outer) core. The data were subdivided into two groups with regard to the magnitude of the environment vertical shear or the translational speed below and above 5 m s$^{-1}$ following Chen et al. (2006).

During the first period (-8 to -3 h before landfall), the maximum WN1 component in the inner core was concentrated to the down shear left (Fig 8a) and the magnitude increased with the intensity of shear (Fig 8b). In the second period under the weaker shear environment, the amplitude of WN1 component was quite small and the signal of shear effect cannot be seen in the inner core (Fig 8c). However with the increased shear intensity, the amplitude of WN1 also increased with the location of maximum to the downshear left (Fig 8d). These characteristics indicated that the effect of vertical wind shear still played an important role in the distribution of rainfall in the inner core of TC in the second period under stronger vertical wind shear.

b. Influence of storm motion

Corbosiero and Molinari (2003) summarized the results in many observational investigations about convection distribution in TC with respect to storm motion and concluded that the precipitation maxima often occurred in the front quadrants within 30 km of the TC center with a weak preference to the right-front in the range of 30 to 100 km. Chen and Yau (2003) pointed that the heavy rain tended to the front side of TC when the TC was approaching coast through a numerical simulation. Based on the aforementioned observational and numerical studies, the front and especially the right-front quadrant is the prime location for heavy rainfall owing to the storm motion effect.
In this investigation, the azimuthal distribution of radial average of radar reflectivity shows that the temporal evolution of strong convection in each TC had little in common with respect to storm motion until around 3 h before landfall (Fig 9). For example, strong convection was concentrated to the right-rear quadrant relative to storm motion in Rananim and Saomai, continuously maintained itself to the front side in Khanun, and rotated clockwise from front to left-rear in Matsa. In Wipha and Krosa, heavy rainfall happened to the rear side all the time before landfall. Starting from about 3 h before landfall, a similar evolution pattern appeared in all TCs’ inner core that increased convection arose in the front side relative to the storm motion until landfall, indicating the effect of land on TC precipitation asymmetry. The blue line in Fig. 9 denotes the distance between the boundary of TC inner core and the coast. The time differences between the inner-core region approaching land and the strong convection arising in the front in each TC preclude the land effect to be the only factor affecting the rainfall distribution. After landfall, the precipitation maxima shifted clockwise to the right-rear quadrant for all TCs.

The corresponding rainfall distributions in the outer-core region are shown in Fig. 10. Except for Matsa, the strong convection all concentrated in the front side, especially in the first quadrant (right-front side) from 8 h before landfall. After landfall, the spatial evolution of precipitation maxima shifted anticyclonically to the right-rear quadrant, similar to that in the inner-core region.

From the normalized radial radar reflectivity profiles, it can be seen from Fig 11a and b that in the first period, in
the outer core the maximum precipitation was located in the front side to the TC center, especially the right-front quadrant, consistent with the azimuth-time chart in Figs. 9-10. In period 2 (Figs. 11c and d), the signal of the storm motion effect was still very obvious in the outer core. The maximum WN1 component occupied a broad arc region in the right-front quadrant. In the inner core, the maximum WN1 asymmetry located to the right rear of storm motion. With the increase of translation speed, the amplitude of precipitation asymmetry weakened. From the first period to the second period, the location of asymmetry maximum showed a slight cyclonic move from right-rear quadrant to the right side, especially in the fast-moving cases (Fig. 11d). The results showed that the distribution of WN1 asymmetry is not completely consistent with the effect of storm motion in the inner core.

The relative importance between storm motion and vertical wind shear on the precipitation distribution is examined. In the inner core during the first period, the intense echoes mostly occurred on the downshear side with a preference to downshear left, implying a strong influence by the vertical wind shear. In the second period, a secondary intense convection appeared in the front quadrants relative to storm motion. However, the vertical wind shear remained as the leading factor based on the distribution of WN1 for both periods. The situation was quite different in the outer-core region. Before landfall, the consistent front-preferred rainfall distribution probably resulted from the effect of storm motion. Jones (1995) proposed, under an adiabatic condition, the isentrope is higher in the down-tilt direction and lower in the up-tilt direction. Since the air stream flows along the isentrope, ascending (descending) motion would occur to the right (left) of the tilt vector. Thus, heavy rainfall would take place to the right of the downshear direction. In the outer core, the impact of vertical shear on the tilt of isentrope may not be as apparent as that in the inner core region. Thus, the primary rainfall asymmetry in the outer core region was most probably a consequence of the
friction asymmetry caused by storm motion (Shapiro 1982). The secondary intense echoes appearing on the downshear right could be a result from the vertical wind shear effect.

c. Influence of topography

The location of strong convection rotated to the right-rear quadrant both in the inner-core and outer-core regions after landfall. This azimuthal rotation cannot be explained by either the effect of storm motion or vertical wind shear.

In order to illustrate this phenomenon more clearly, the frequency of heavy rainfall (≥40 dBZ) occurrence in the period concerned of each TC was examined in this study. As illustrated in Fig. 12, most of the high values of heavy rain frequency (HRF) were located to the right of the TC tracks over land along the coastline. Therefore, there might be some correlation between the intense convection and the topography to the right of TC track along the coast.

The radar reflectivity along two line segments across the TC tracks of Rananim and Saomai were examined to investigate the temporal variation of the precipitation near the coast. The ~90 km line segment AB (Fig. 12a) and CD (Fig. 12d) were selected paralleling to the coast. In Rananim (Fig. 13a), the terrain height to the right of the track was nearly 650 m above sea level while there was almost no terrain to the left. And the situation was different in Saomai (Fig. 13b) with high mountains (about 620 m) lying to the left of the track and much lower terrains to the right. Starting from 8 h before landfall, a narrow band of strong reflectivity skimmed through the line segment very quickly, which was consistent with the feature observed by Smith and Schafer (2009) in Hurricane Dean (2007) passing through mountainous areas. After that, the precipitation became more and more asymmetric with stronger convection continuously generating in the area of mountain peaks to the right while the reflectivity remained weak to the left. The evolution of reflectivity was quite similar in Saomai that heavy rainfall persisted to the right of the track. This enhanced precipitation was quasi-stationary, which seemed to be quite different from the fast-moving precipitation brought by the passage of TC rainband. Thus, the overlap-
ping location with mountain peak and the quasi-stationary characteristic suggested that the enhanced precipitation was a direct consequence of the orographic forcing.

Given the strong dependence of topographic lifting on the surface wind and the terrain gradient, the effect of topography was represented by a simplified expression:

\[ F_{\text{topography}} = \vec{V} \cdot \nabla h \]  

\[ (2) \]

Where \( \vec{V} \) is the surface wind at 1200 UTC 12 August, and \( h \) is the terrain height. The results are shown in Fig. 14. The mean reflectivity from 1200 -1300 UTC showed that the precipitation in typhoon enhanced over the positive \( F_{\text{topography}} \). The precipitation maximum was located on the downwind direction of the \( F_{\text{topography}} \) maximum center probably due to advection. This reflectivity pattern illustrated the influence of topographic lifting on the enhancement of precipitation and the distribution of intense rainfall.

5. Summary

The effects of storm motion, vertical wind shear and topography on precipitation distributions were investigated within 6 landfalling TCs along the southeast China coast between 2004 and 2007. The radar reflectivity from the Wenzhou and Wu-Fen Shan radars are decomposed via a Fourier analysis to extract the low-order wavenumber components. There were notable asymmetries in landfalling TC precipitation both in the inner-core and outer-core regions and the amplitude of asymmetry had a negative correlation with the TC intensity. In the inner core, the WN1 accounted for most of the asymmetries and the precipitation became more axisymmetric during the landfall. In the outer-core regions, appreciable WN2 component could be comparable to WN1 component when the storm was under an environment of strong vertical wind shear and the amplitude of precipitation asymmetries increased during the course of landfall.

From -8 to -3 h before landfall, intense echoes in the inner core appeared primarily on the downshear side with a little azimuthal shift, consistent with the influence by the vertical wind shear. Subsequently, strong convection generated in the front side with respect to storm motion at around...
Fig. 12. Frequency distribution (shading) of heavy precipitation (>40 dBZ) during landfalling (8h before landfall to 6h after) for (a)Rananim, (b)Matsa, (c)Khanun, (d)Saomai, (e)Wipha and (f)Krosa. The black solid lines are topographic contours with a contour interval of 300 m and the red line is typhoon track.

Fig. 13. Time variation of radar reflectivity (shading) along selected segment. (a)Rananim, (b)Saomai. The horizontal line denotes the landfall time while the curve reveals distances between TC center and coast. Solid line in lower portion of each panel indicates terrain height.
3 h before landfall implying the increasing influence of storm motion on the precipitation distribution. However, the results of Fourier decomposition illustrated that the impact of the strong vertical shear remained dominant for precipitation distribution in the inner core. In the outer core, the precipitation maxima resided in the right-front quadrant in all cases indicating a more significant correlation between precipitation distribution and the storm motion. A secondary maximum echo band to the downshear right may be affected by the vertical shear.

After landfall the location of precipitation maxima rotated anticyclonically to the right-rear quadrant both in the inner-core and outer-core regions. The locations of the coastal mountains relative to the TC center as a function of time were the foci of the continuous heavy rainfall, may explain this anti-cyclonic shift of intense echo. The impact of terrain on precipitation enhancement and distribution in typhoons can be illustrated by the heavy rainfall located to the downwind direction of quantified topographic lifting maximum.

In summary, the precipitation distribution of a landfalling TC is determined by the combination of storm motion, vertical wind shear and topography effect. Before landfall, the effect of shear dominates the rainfall pattern in the inner core while the effect of storm motion plays a more important role in the outer core. The topographic enhancement determines the heavy rainfall occurrence after TC’s landfall. The generality of the results revealed in this study will be examined with more landfalling TCs in the future studies.

Acknowledgments
This work was primarily supported by the Social Common wealth Research Program (GYHY201006007), the National Natural Science Foundation of China (grants 41275031, 40975011 and 40921160381), and National Fundamental Research 973 Program of China (2013CB430101).

References
Chan, J. C. L. and K. S., Liu, 2004: Asymmetric Distribution of Convection Associated with Tropical Cyclones Making Land-


Zhang J., S. Wang, B. Clarke, 2004: WSR-88d reflectivity quality control using horizontal and vertical reflectivity structure/Preprints, the 11th Conference on aviation, range and aerospace meteorology, AMS, P5.4.