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A COMPOSITE STUDY OF RAINFALL ASYMMETRY OF TROPICAL CYCLONES AFTER MAKING LANDFALL IN GUANGDONG PROVINCE

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Abstract: Based on observed rainfall data, this study makes a composite analysis of rainfall asymmetry in tropical cyclones (TCs) after making landfall in Guangdong province (GD) during 1998—2015. There are 3.0 TCs per year on average making landfall in GD and west of GD (WGD) has the most landfall TCs. Most of TCs make landfall in June, July, August, and September at the intensities of TY, STS, and TS. On average, there is more rainfall in the southwest quadrant of TC in CGD (center of GD), WGD, and GD as a whole, and the maximum rainfall is located in the southwest near the TC center. The mean TC rainfall in the east of GD (EGD) leans to the eastern side of TC. The TC rainfall distributions in June, July, August, and September all lean to the southwest quadrant and the maximum rainfall is located in the southwest near the TC center. The same features are found in the mean rainfall of TD, TS, STS, TY, and STY. The maximum rainfall is mainly in the downshear of vertical wind shear. Vertical wind shear is probably the dominate factor that determines asymmetric rainfall distribution of TCs in GD. Storm motion has little connection with TC rainfall asymmetry in GD.

Key words: rainfall asymmetry; tropical cyclone; landfall
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1 INTRODUCTION

Tropical cyclone (TC) is one of the most intense and feared storms of the world for its strong wind and extreme heavy rainfall. TCs can cause vast disaster and tremendous damage in coastal areas when making landfall. One of the disaster-causing factors for landfall TCs is the heavy rainfall, which may lead to widespread inland flood and other secondary disasters such as mud-rock flows. TCs often bring about extreme rainfall. Lots of extreme rainfall events are related to TCs (Dong et al.[1]; Chen et al.[2]; Yu et al.[3]). The highest daily rainfall record in China, which is 1,748.5 mm, is associated with the super typhoon Herb (9602) when passing Taiwan Island (Chen et al.[2]). Extreme rainfall is easy to result in disaster. In August 8, 2009, super typhoon Morakot made landfall in Taiwan Island and brought about 1,623.5 mm daily rainfall in Ali Mountain. This heavy rainfall triggered flood and mud-rock flows, causing large losses of human lives and property (Chen et al.[2]). The regions that suffer most are largely determined by the rainfall distribution of TCs. Therefore, knowing the spatial distribution of rainfall in a landfall TC is crucial in rainfall forecast and disaster mitigation.

Many observations (Yu et al.[4]; Xu et al.[5]; Yuan et al.[6]; Wingo and Cecil [7]; Liu et al.[8]; Chen et al.[9]; Lonfat et al.[10]; Chan et al.[11]; Chan and Liang[12]; Huang et al.[13]; Zhou et al.[14]; Lv et al.[15]) have shown that TCs exhibit significant rainfall asymmetries over the ocean or after making landfall. The rainfall of TCs is generally not symmetrically distributed, and is usually more pronounced on some parts of TCs than the others. It is beneficial to find out the location that experiences the heaviest rainfall. Early studies (Rodgers et al.[16]; Burpee and Black[17]) revealed that TCs over the ocean have a precipitation maximum in the front quadrant (front-right or front-left) of the storm. Lonfat et al. recently found a similar result: the maximum rainfall for the global average of all TCs is located in the front quadrants, and the location of the maximum rainfall is in the front-left quadrant for tropical storm and in the front-right for hurricane or typhoon[10]. This kind of asymmetry is related to friction-induced asymmetric boundary layer convergence caused by storm motion (Lonfat et al.[10]; Shapiro[18]). However, some studies (Jones[19]; Tuleya and Kurihara [20]; Chen et al.[21]; Yu et al.[22]) found that the right side of track favors more rainfall when a TC makes landfall. As a TC approaches (Huffman et al.[23]) land, surface friction gradient between land and sea induces a frictional convergence to the right side of the

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storm motion in the Northern Hemisphere (Xu et al.[5]). Recently, more and more studies(Yu et al.[4]; Xu et al.[5]; Yuan et al. [6]; Wingo and Cecil [7]; Chen et al. [9]; Corbosiero and Molinari [24]; Chen and Fang [25]) found that the asymmetric distribution of TC rainfall is more related to the vertical wind shear. These studies showed that a maximum of convection and rain rate occurs at the downshear or left-of-shear of vertical wind shear. The conceptual model is that updrafts, initiated downshear by a shear-induced tilt of the TC vortex, are wrapped cyclonically around the core by the rapidly rotating tangential winds, and create a maximum vertical motion in the downshear to downshear left quadrant (Rogers et al. [26]). Maximum precipitation is displaced farther counterclockwise through advection. Some studies (Yu et al.[4]; Xu et al.[5]) pointed out that environmental vertical wind shear is the dominant factor that produces TC rainfall asymmetry comparing to other factors.

The south China coast is one of the coastlines around the world that are most frequently affected by TCs (Chan et al.[11]). Guangdong (GD), in the south of China, is the province visited by most tropical cyclones (TCs) making landfall in China. There are 3.9 landfall TCs on average in GD every year, with the largest number of 7 in the years of 1952, 1961, 1967 and 1993 (Wrinting Group of Guangdong Meteorological Service [27]). Landfall TCs frequently cause great losses to GD every year due to their rainfall. Therefore it is necessary and beneficial to study the rainfall distribution of TCs making landfall in GD. Since the most significant impact of TC rainfall occurs when a TC has moved to land, this study investigates the rainfall asymmetry of TCs after making landfall in GD and the relation with vertical wind shear and storm motion.

2 DATA AND METHOD

2.1 *Data*

The best track dataset used is taken from Shanghai Typhoon Institute, China Meteorological Administration (CMA). This dataset provides the TC center location, TC intensity, and other important parameters of TCs every 6 hours.

Two kinds of precipitation data are used in this study. The first kind of precipitation data is Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) 3B42 precipitation product version 7 (Huffman et al. [23]). TRMM 3B42 product has 3-hourly temporal resolution and 0.25° × 0.25° spatial resolution, covering the globe from 50°S to 50° N, available from 1998 to the present. Previous studies (Chen et al.[28]; Yu et al.[29]; Jiang et al.[30]; Jiang et al. [31]) have shown that the TRMM 3B42 product could give quite reasonable rainfall patterns in landfall TCs when compared with the gauge data or radar estimates. The second kind of precipitation data is merged analysis of precipitation product version 1.0 in which rainfall observation from automatic meteorological stations of CMA are merged with CMORPH data (Joyce et al. [32]). It is referred to as CMORPH-CN in this study for convenience. CMORPH-CN data is hourly and this data starts from 2008. This dataset is on a 0.1°×0.1° latitude/longitude grid, covering China and its surrounding areas (70.05°E—139.95°E, 15.05°N—58.95°N).

ERA Interim reanalysis data (Dee and Uppala [33]) from European Centre for Medium-Range Weather Forecasts is used to calculate mean environmental vertical wind shear in this study. Only the meridional and zonal winds at 850- and 200-hPa levels are extracted. The horizontal resolution of the data is 1.0°× 1.0° and the temporal resolution is 6-hourly.

2.2 *Method*

GD has a long coastline and can be attacked by TCs at any location (Fig.1). The coastline is customarily divided into three coastal areas (Fig.1): east of GD (EGD hereafter, which is from Raoping to Haifeng), center of GD (CGD hereafter, which is from Huidong to Taishan), and west of GD (WGD hereafter, which is from Yangjiang to Xuwen). Accordingly, the TCs making landfall in GD are mainly classified into three categories according to the landfall sites[27]. In this study, the landfall sites of TCs are manually determined by checking the storm tracks (Fig.1). Another parameter related to landfall TCs is the landfall time. Most of the time, the landfall time of TCs does not match with the recorded time in the best track data, since the TC center is located every 6 hours. If the landfall time of a TC does not agree with the recorded time (or locating time), the nearest recorded time is regarded as landfall time. For example, if a TC makes landfall at 07:00 (10:00), 6:00 (12:00) is regarded as landfall time. This study focuses the rainfall asymmetries of TCs after making landfall. However, the TC weakens quickly after landfall to the intensity that the operational organization stops locating the TC center. Hence, only the rainfall at the time of TC making landfall and 6 hours later after making landfall is selected to study the TC rainfall asymmetry in GD.

Following Xu et al. and Lonfat et al., the grid rainfall data are interpolated into storm-relative coordinate to show the rainfall distribution of TCs, since the centers of TCs are not the same [5,10]. The coordination is centered at TC center and has 10-km-width annuli around the storm center outward to the 500-km radius and 1-degree-width azimuth. After interpolation, the rainfall for every TC is in the same coordinate system, and it is convenient to make composite analysis for the rainfall distribution of TCs.

Vertical wind shear is computed following the methodology of Hanley et al.[34]. That is, the zonal and meridional winds are first interpolated onto a 100 km× 22.5° azimuth polar grid centered on the storm center outward to 500 km for the 850- and 200-hPa levels.

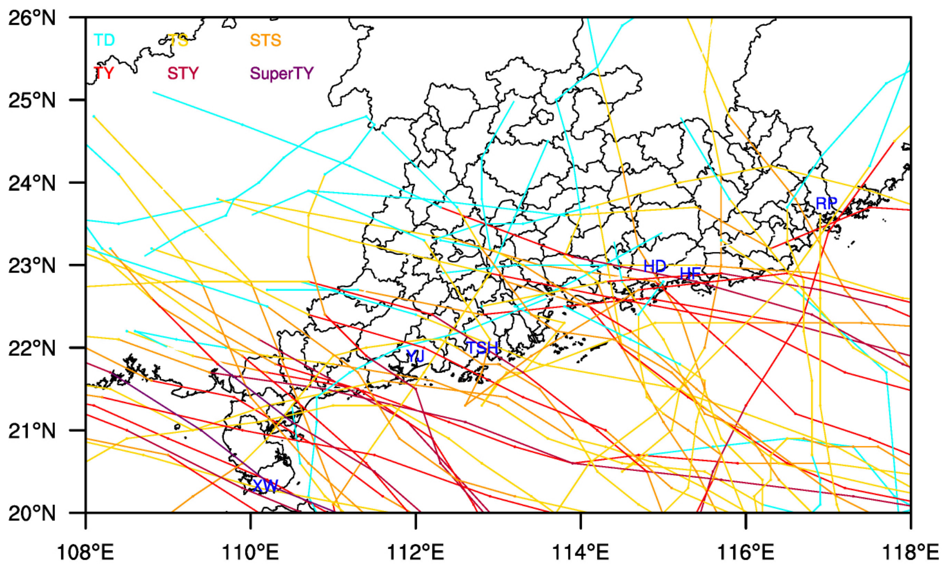

Figure 1. Tracks of tropical cyclones making landfall in GD during 1998—2015. Blue texts denote the counties of Raoping (RP), Haifeng (HF), Huidong (HD), Taishan (TSH), Yangjiang (YJ), and Xuwen (XW).

These winds are then averaged over a radius of 500 km from storm center to remove symmetric vortex so that the winds provide a better measure of the environmental flow across the storm. The 200-850-hPa vertical wind shear is then calculated from these area-averaged winds over the inner 500 km of the radius. This methodology was widely used in studies (Chan and Liang[12]; Hanley et al.[34]; Qian et al.[35]).

Storm motion vector is calculated from TC center position in best track data using a 6-hour centered differencing scheme. For a selected time, the storm motion vector is the average of the past and next 6-hour storm motion vectors. If there is no TC center position 6 hours later or ago in the best track data, the past or next 6-hour storm motion vector is regarded as the storm motion vector for a selected time.

3 RESULTS

3.1 *Statistical characteristic of TCs making landfall in GD*

Statistical analysis is firstly carried out to reveal the regional and seasonal distribution of TCs making landfall in GD. There are 54 TCs making landfall in GD during 1998—2015, equivalent to 3.0 landfall TCs per year on average. These TCs make landfall in different sites of the coastline. However, more TCs make landfall in WGD, and EGD has the least landfall TCs, which is consistent with the statistical result based on landfall TCs during 1949—1998[27]. The landfall TCs in WGD, CGD, and EGD account for ~39%, ~33%, and ~28% of the total respectively (Fig.2a). On average, there are 1.2, 1.0, and 0.8 TCs landing in WGD, CGD, and EGD per year (Fig.2a).

TC season is quite long for GD, and more than half of a year have landfall TCs. TCs making landfall in

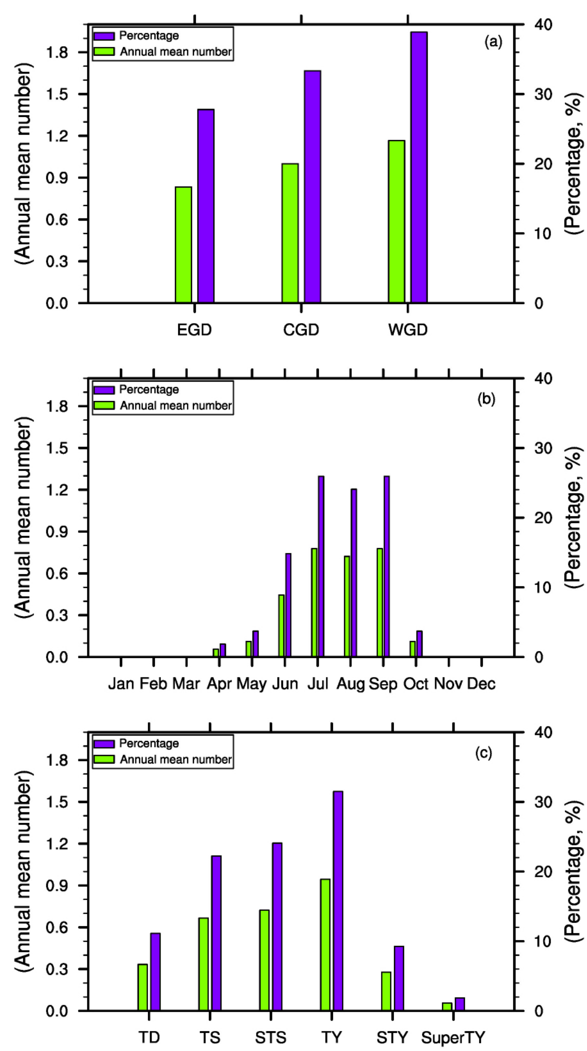

Figure 2. Annual mean number (green bar) and percentage (purple bar) of TCs in different (a) regions, (b) months, and (c) intensities.

GD in the 18 years mainly happen from April to October. There are no landfall TCs in the rest of a year during 1998—2015. However, the seasonal difference is obvious. Most of TCs make landfall in June, July, August, and September (Fig.2b). Up to 49 of the 54 TCs making landfall occur in June, July, August, and September during 1998—2015. There are only 5 landfall TCs in total in April, May, and October in the 18 years.

The landfall TCs could be at various intensities when they are making landfall. Most of the TCs are at the intensities of typhoon (TY), severe tropical storm (STS), and tropical storm (TS), accounting for ~31.5%, ~24.1%, and ~22.2% of the total, respectively (Fig.2c). Only about 11% of the landfall TCs are severe typhoon (STY) or super typhoon (SuperTY).

In general, TCs could land anywhere along the coastline of GD, and WGD has the most landfall TCs. Most of TCs make landfall in June, July, August, and September at the intensities of TY, STS, and TS.

3.2 *The mean rainfall asymmetries of TCs after making landfall*

We analyze the mean rainfall distribution of TCs after making landfall in different parts of GD, which are shown in Fig.3. The rainfall distribution of TCs making landfall during the period of 1998—2015 is firstly derived from TRMM 3B42 product (Fig.3a-d). As can be seen from Fig.3a-d, there are clear TC rainfall asymmetries in GD. For the TCs making landfall in GD as a whole, more rainfall occurs in the southwest quadrant of TC, and the maximum rainfall is located in the southwest near the TC center (Fig.3a). The quadrant-averaged rainfall also indicates that the southwest quadrant has the most rainfall, about double the rainfall in the northeast or northwest quadrants (Fig. 4a). Similar asymmetric rainfall distribution is found as well for the TCs in CGD and WGD, where the rainfall distribution mainly leans to the southwest quadrant of TCs and the maximum rainfall is in the southwest near the TC center (Fig.3c-d, Fig.4a). However, the rainfall leans toward the eastern side of TCs in EGD (Fig.3b, Fig.4a), which is different from the TC rainfall distribution in CGD and WGD. In addition, the CMORPH-CN data that has merged with surface rainfall observation is used to verify the rainfall asymmetry of landfall TCs. There are similar asymmetric features with those from the TRMM 3B42 product, in spite of different periods and different rainfall data. The TC rainfall leans to the southwest quadrant of TC in CGD, WGD and GD as a whole, and eastern side of TC in EGD (Fig.3e-h, Fig.4b). The maximum rainfall is located in the southwest near the TC center for the landfall TCs in CGD, WGD, and GD.

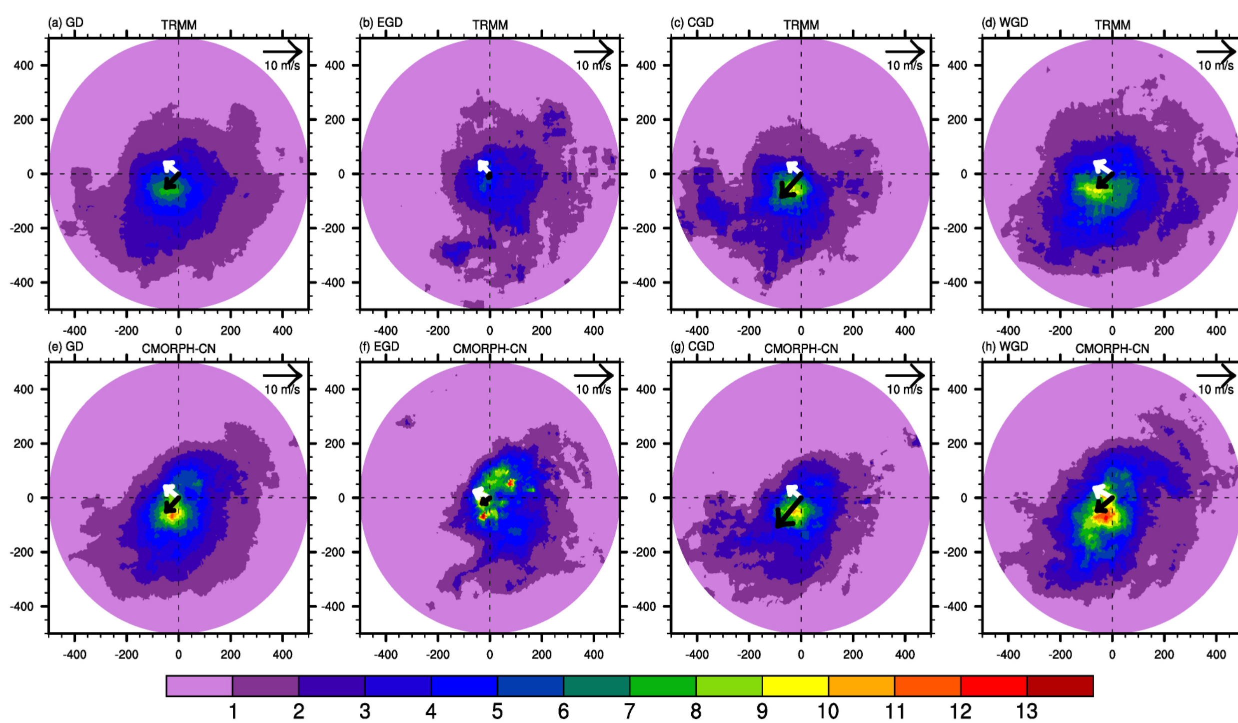

Figure 3. The top row (a-d) are the distribution of TC rainfall (mm/h) after making landfall averaged in 1998—2015 for (a) GD, (b) EGD, (c) CGD, and (d) WGD derived from TRMM 3B42 product. The bottom row (e-h) are the same, but averaged in 2008—2015 derived from CMORP-CN data. Black and white arrows represent vertical wind shear (200—850 hPa) and storm motion, respectively.

The rainfall asymmetries of landfall TCs in different months are investigated as well. Earlier analysis indicates that most of the TCs made landfall in June, July, August, and September, and only 5 landfall TCs in total occurred in April, May, and October during the period of 1998—2015. Therefore, the analysis only

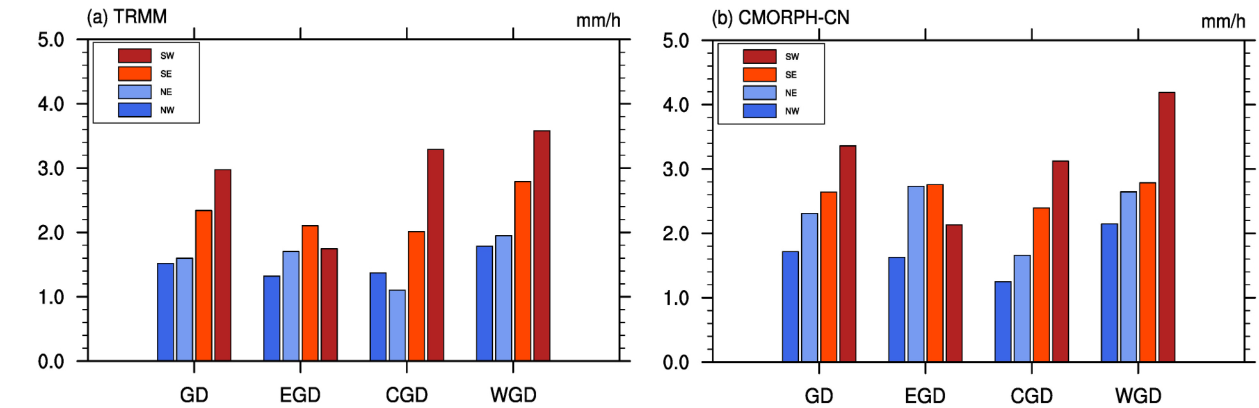

Figure 4. Quadrant-averaged rainfall (mm/h) of landfall TCs in GD, EGD, CGD, and WGD using (a) TRMM data (1998—2015) and (b) CMORPH-CN data (2008—2015). NW, NE, SE, and SW represent the northwest, northeast, southeast, and southwest, respectively.

focuses on the mean TC rainfall asymmetries in June, July, August, and September. Fig.5a-d shows that the TC rainfall distributions in the four months all have the same asymmetric feature, that is, the TC rainfall leans to the southwest quadrant and the maximum rainfall is located in the southwest near the TC center. This feature is more obvious from the comparison of the quadrant-averaged rainfall in Fig.6a. The rainfall of landfall TCs in June, July, August, and September during 2008—2015, based on CMORPH-CN data, has the same asymmetric distributions with that during 1998—2015 derived from the TRMM 3B42 product (Fig.5e-h, Fig.6b). Both datasets indicate that there is more rainfall in the southwest quadrant of TC in the TC season.

Some studies (Xu et al.[5]; Lonfat et al.[10]) indicated that the magnitude of rainfall asymmetry decreases as the TC intensity increases, and STY or SuperTY have nearly symmetric rainfall distribution. In order to reveal the relation between rainfall asymmetry and TC intensity in GD, we analyze the rainfall distribution of TCs at different intensities. The rainfall distribution of SuperTY is not analyzed, since there are only two samples during 1998—2015. Fig.7 shows the mean rainfall distributions of TCs at the intensities of TD, TS, STS, TY, and STY based on TRMM 3B42 product and CMORPH-CN data, respectively. In general, the TC rainfall asymmetry decreases with increasing TC intensity (Fig.7). Nevertheless, the rainfall still has significant asymmetric distribution for TCs at each

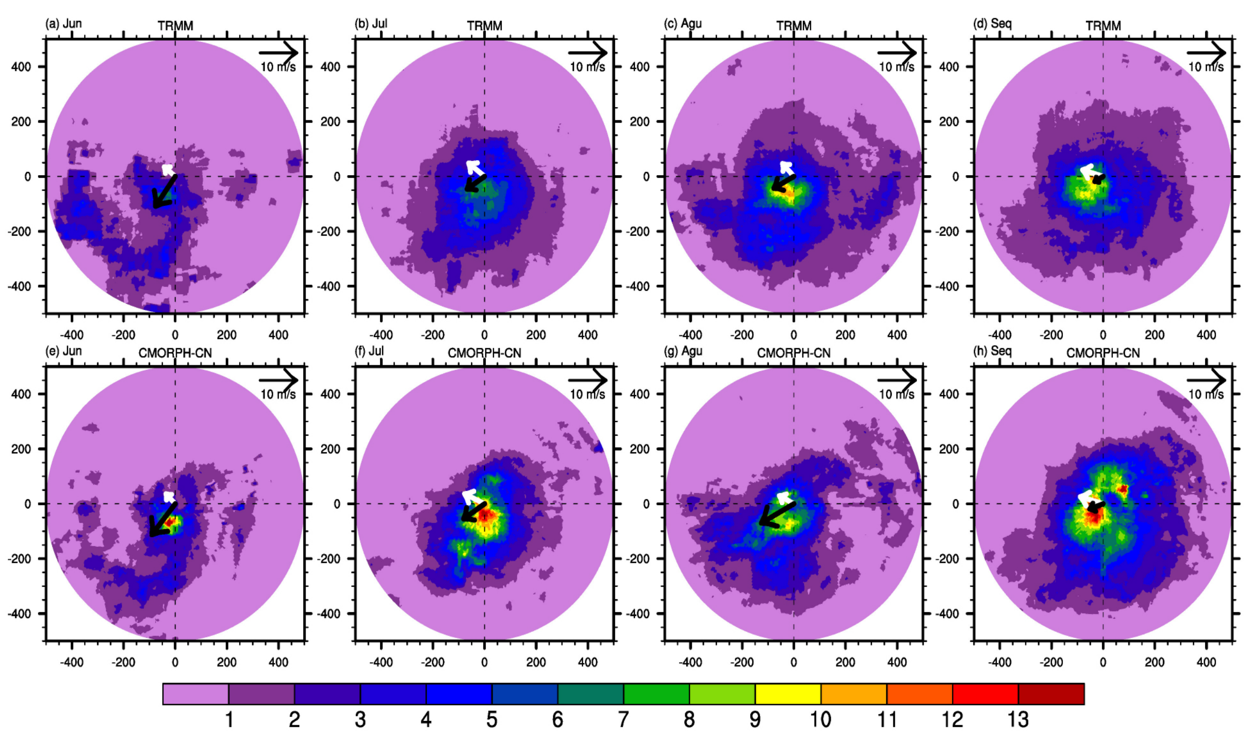

Figure 5. Same as Fig.3, but for the rainfall distribution of TCs in June, July, August, and September.

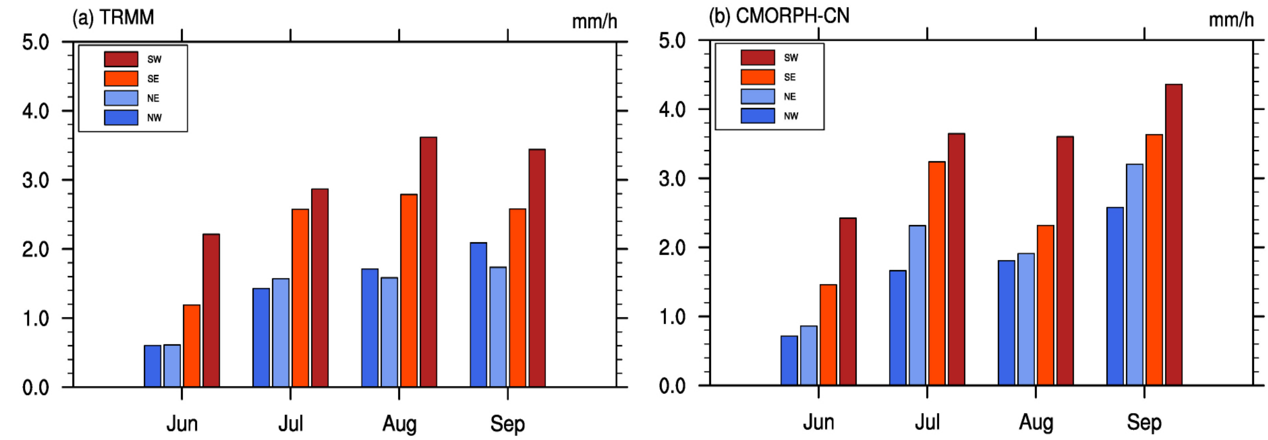

Figure 6. Same as Fig.4, but for the quadrant-averaged rainfall of TCs in June, July, August, and September.

intensity. Same as the features in regional and seasonal analysis, there are more rainfall in the southwest quadrant for TCs at each intensity (Figs.7 & 8). The maximum rainfall of TS, STS, TY, and STY are all located in the southwest quadrant near the TC center (Fig.7).

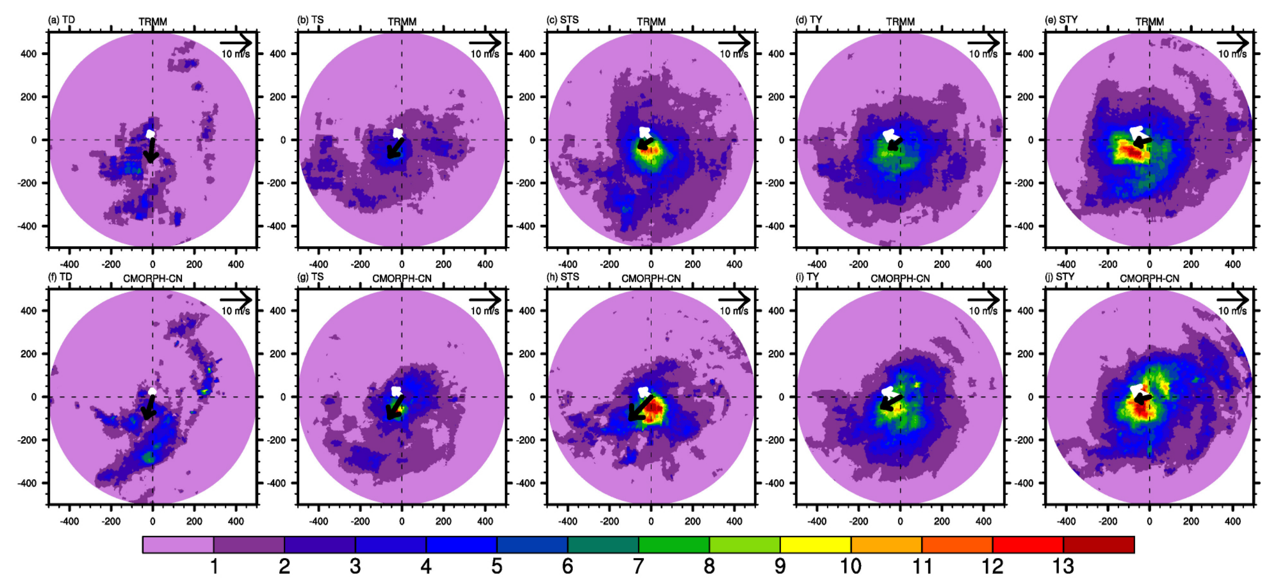

Figure 7. Same as Fig.3, but for the rainfall distribution of TCs at the intensity of TD, TS, STS, TY, and STY.

3.3 *The relation of rainfall asymmetry of TCs with storm motion and vertical wind shear*

Chen et al. pointed out that storm motion and vertical wind shear are the two main factors that influence the TC rainfall distribution [9]. There is more rainfall at the front quadrant (front-left or front-right) when TC rainfall is related with storm motion, and in the downshear when TC rainfall is associated with environmental vertical wind shear. Hence, we mainly investigate the relations between rainfall asymmetry and these two factors for the landfall TCs in GD. The storm motions and vertical wind shears are also calculated when we make composite analysis of the TC rainfall distributions. The storm motions and vertical wind shears are depicted with white and black arrows in Figs. 3, 5 and 7, respectively.

Figure 3 indicates that storm motions are all northwestward for the landfall TCs in GD including EGD, CGD, and WGD. However, the maximum rainfall is not at the front quadrant of TC in any region. On the contrary, the maximum TC rainfall in GD, CGD, and WGD is located in the downshear of vertical wind shears, which are southwestward. The vertical wind shear is weak in EGD, so the maximum rainfall is not located in the southwest quadrant as those in CGD and WGD. The relation between asymmetric distribution of TC rainfall and the two factors in different regions of GD indicates that vertical wind shear is related with the TC rainfall asymmetry. The relation in different months further implies the importance of vertical wind shear on the TC rainfall asymmetry. The rainfall of TCs leans to the southwest quadrant in June, July, August, and September, and meanwhile the vertical wind shear is all southwestward (Fig.5). The maximum rainfall is in the downshear of vertical wind shear. Storm motion has no obvious connection with the rainfall asymmetry in each month as well, since maximum rainfall is not at the front quadrant (Fig.5). There are the same close relationship between rainfall distribution and vertical wind shear for TCs at different intensity. The maximum rain generally leans to the downshear of vertical wind shear, which is southwestward (Fig.7).

Rogers et al. suggested that the vertical wind shear can induce the tilt of TC vortex and updrafts are initiated downshear [26]. The rapidly rotating tangential winds of TC wrap the updrafts cyclonically around the core. Thus the maximum vertical motion and maximum rainfall is in the downshear to downshear left (Rogers et al.[26]). The vertical wind shear is the main factor that determines the TC rainfall distribution in GD. As shown in Figs.3, 5, and 7, vertical wind shears in GD are generally southwestward. Therefore, the maximum rainfall is in the southwest quadrant.

4 SUMMARY

In this study, we make a composite analysis of the rainfall asymmetry in TCs after making landfall in GD and their relation with storm motion and vertical wind shear based on TCs during 1998—2015.

The statistical characteristic of landfall TCs during 1998—2015 is revealed. There are 3.0 TCs per year on average (54 in total) making landfall in GD and WGD has the most landfall TCs (~1.2 per year) and EGD has the least (~0.8 per year). Most of TCs make landfall in June, July, August, and September at the intensities of TY, STS, and TS. Up to 49 of the 54 landfall TCs occur in June, July, August, and September, and 42 of the 54 landfall TCs are at the intensities of TY, STS, and TS during 1998—2015.

We analyze the rainfall asymmetry of landfall TCs in the different regions, different months and different intensities. There is more rainfall in the southwest quadrant of TC in CGD and WGD, and the maximum rainfall is located in the southwest near the TC center. The TC rainfall in EGD leans to the eastern side of TC. The asymmetric features of landfall TCs in GD as a whole are the same as those of CGD and WGD. The mean TC rainfall distributions in June, July, August, and September all have the same asymmetric feature, that is, the rainfall leans to the southwest quadrant and the maximum rainfall is located in the southwest near the TC center. The same features are found in the rainfall of TD, TS, STS, TY, and STY.

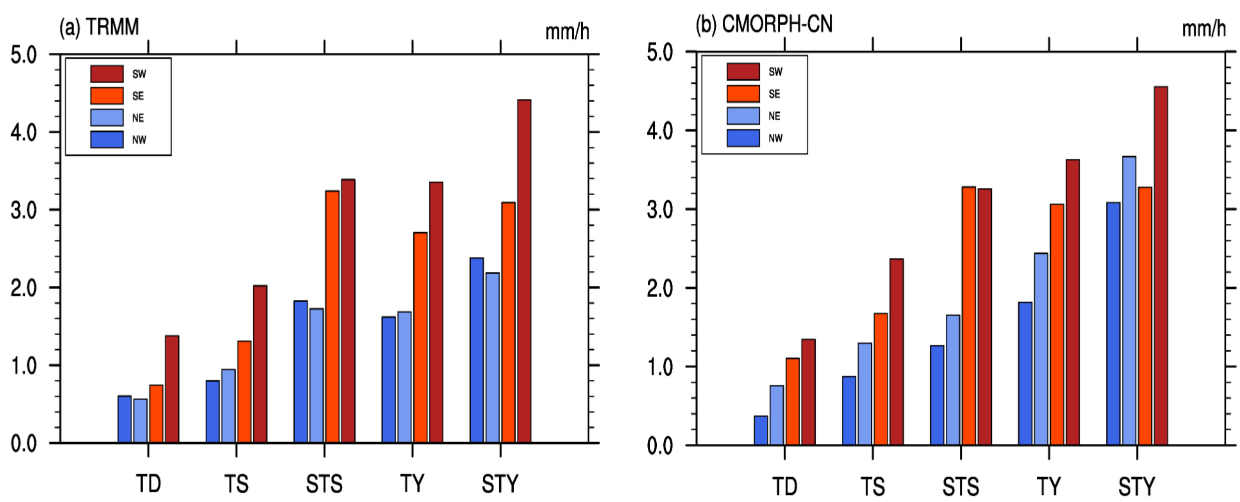

Figure 8. Same as Fig.4, but for the quadrant-averaged rainfall of TCs at the intensity of TD, TS, STS, TY, and STY.

The relations between TC rainfall asymmetry and storm motion and vertical wind shear in GD are further investigated. The storm motion is northwestward, but the maximum rainfall is not in the front quadrant, indicating that storm motion has little connection with the rainfall asymmetry in GD. Nevertheless the vertical wind shear is probably the main factor that determines asymmetric rainfall distribution of TCs in GD. The vertical wind shear is southwestward, and the maximum rainfall is mainly in the downshear.

This study provides an overview of rainfall distribution of landfall TCs in GD. The asymmetric feature of TC rainfall and their relation with vertical wind shear are of benefit to TC rainfall prediction in GD.

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