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AN OBSERVATIONAL STUDY ON DISTRIBUTION OF PRECIPITATION ASSOCIATED WITH LANDFALLING TROPICAL CYCLONES AFFECTING CHINA

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Abstract: In order to provide an operational reference for tropical cyclone precipitation forecast, this study investigates the spatial distributions of precipitation associated with landfalling tropical cyclones (TCs) affecting China using Geostationary Meteorological Satellite 5 (GMS5)-TBB dataset. All named TCs formed over the western North Pacific that made direct landfall over China during the period 2001–2009 are included in this study. Based on the GMS5-TBB data, this paper reveals that in general there are four types of distribution of precipitation related to landfalling TCs affecting China. (a) the South-West Type in which there is a precipitation maximum to the southwestern quadrant of TC; (b) the Symmetrical South Type in which the rainfall is more pronounced to the south side of TC in the inner core while there is a symmetrical rainfall distribution in the outer band region; (c) the South Type, in which the rainfall maxima is more pronounced to the south of TC; and (d) the North Type, in which the rainfall maxima is more pronounced to the north of TC. Analyses of the relationship between precipitation distributions and intensity of landfalling TCs show that for intensifying TCs, both the maximum and the coverage area of the precipitation in TCs increase with the increase of TC intensity over northern Jiangsu province and southern Taiwan Strait, while decreasing over Beibu Gulf and the sea area of Changjiang River estuary. For all TCs, the center of the torrential rain in TC shifts toward the TC center as the intensity of TC increases. This finding is consistent with many previous studies. The possible influences of storm motion and vertical wind shear on the observed precipitation asymmetries are also examined. Results show that the environmental vertical wind shear is an important factor contributing to the large downshear rainfall asymmetry, especially when a TC makes landfall on the south and east China coasts. These results are also consistent with previous observational and numerical studies.

Key words: distribution of precipitation; tropical cyclone; landfall; western North Pacific

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1 INTRODUCTION

Spatial distribution of rainfall in landfalling tropical cyclones (TCs) is of particular interest for the quantitative precipitation forecast (QPF). While a TC spends most of its life-time over the open ocean and poses a threat to ocean vessels, most damage occurs along the coastal areas during its landfall through its strong winds, heavy rain, and storm surge. One of the most destructive elements for landfalling TCs is the torrential rain that causes widespread flooding. Understanding the spatial distribution of the precipitation associated with the landfalling TCs, especially the region where the heaviest precipitation is located, is therefore crucial in both QPF for landfalling TCs and disaster mitigation. This study attempts to document the general changes in precipitation distribution associated with TCs prior to, during, and after landfall.

As a TC approaches land, asymmetric wind and

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rainfall distribution may develop because of differential forcing between land and ocean. Earlier studies based on rain gauge data suggested that coastal rainfall was more pronounced to the right of the track of Northern Hemisphere TCs[1, 2], although results[2] showed that the difference in rainfall between the left and right sides of the storm was insignificant. A numerical study[3] also showed that the location of maximum precipitation existed in the forward-right quadrant of the storm during and after landfall. Jones[4] and Powell[5] gave similar results: more rainfall occurred to the right of the storm than to the left at landfall. However, a recent study by Chan and Liang[6] showed a precipitation maximum to the front and left quadrants of the TC prior to landfall. Their more recent observational study[7] investigated the asymmetric distribution of convection associated with landfalling TCs and showed that the enhanced convection generally occurred to the western side of the TC before landfall, which was consistent with their former study.

Many mechanisms were proposed to explain the asymmetric rainfall distribution associated with landfalling TCs. Dunn and Miller[8] explained that differential surface friction between land and ocean would induce a frictional convergence (divergence) to the right (left) of a landfalling TC in the Northern Hemisphere, which is apparent in various observational studies[5, 9] as well as numerical studies[3, 4]. However, frictional convergence cannot be the only determining factor for the coastal rainfall maximum. Other factors, from large-scale environmental situations to small-scale local topographic effects, have to be taken into account. In fact, intense convective cells, which probably account for the rainfall maxima, are often observed to be more pronounced to the left of the TC track[10, 11]. Rogers et al.[12] found that the combination effect of vertical wind shear and storm motion is critical in explaining the rainfall asymmetry in Hurricane Bonnie (1998). An along-track shear resulted in a symmetric rainfall accumulation, whereas a cross-track shear created a right-side asymmetry in the accumulated rainfall as Bonnie approached the U.S. east coast. The case studies by Chan et al.[7] also showed the determinant influences of vertical wind shear on the observed convective asymmetries associated with four TCs over western North Pacific. Corbosiero and Molinari[13] suggested that the environmental shear is a dominant factor modulating the downshear-left convective activity in hurricanes. These observational results were consistent with the numerical results[14, 15] in that shear excited a steady wavenumber-1 asymmetry in the vertical motion field with ascent on the downshear-left side of the shear vector, enhancing convection, and descent on the upshear-right side, suppressing convection.

The previous observational and modeling studies provide some evidence of the effects of environmental shear and storm motion on TC asymmetries in terms of storm structure and rainfall over the Atlantic or in idealized conditions. The generality and complexity of the TC rainfall asymmetry over the western North Pacific are not very clear. We will address these issues by examining the spatial distributions of rainfall associated with landfalling TCs and their relationships to the environmental flow with the focus on vertical wind shear in this study. We will also investigate how these relationships vary for different TC intensity groups. The details and analysis methodology of the data are described in section 2. Results from the analyses are presented in sections 3 and 4. Although limited data availability precludes a detailed study of the physical processes responsible for such asymmetries, some possible relationships between the rainfall asymmetries and the large-scale vertical wind shear and storm motion are examined in section 5. A summary and conclusions are given in section 6.

2 DATA AND METHODS

2.1 *Data*

The retrieved hourly precipitation dataset of 0.05° resolution for landfalling TCs was obtained from Shanghai Typhoon Institute of China. This dataset was set up based on the Geostationary Meteorological Satellite 5 (GMS5) infrared images (IR1 channel; 10.1–11.65 um) TBB by the method of QPE for landfalling TCs [16, 17], considering the GMS5-TBB characteristics, hourly precipitation intensity, and horizontal distribution for landfalling TCs. The ability of the GMS5-TBB retrievals in reflecting precipitation features related to landfalling TCs was evaluated by Yu et al.[18]. They showed that the GMS5-TBB retrieved dataset is very useful as a research reference for investigating the heavy rainfall features associated with landfalling TCs.

The TC data over the western North Pacific during the period 2000–2009 were obtained from the China Meteorological Administration (CMA), including the positions (0000, 0600, 1200, and 1800 Coordinated Universal Time, or UTC) and maximum sustained wind speed for each 6-h interval.

The vertical wind shear was computed from the daily National Center for Environmental Prediction (NCEP, USA) reanalysis data, which have a spatial resolution of 1°×1° and a temporal resolution of 6 h. The difference between the horizontal wind fields at the 200-850 hPa levels is calculated and then averaged over a radius of 800 km from the storm center.

2.2 *Methodology*

To investigate the detailed precipitation features related to landfalling TCs affecting China, the study area is first divided into thirty 4° latitude by 4° longitude boxes, which are shown in Figure 1. For each box, the composite precipitation field is then obtained by averaging precipitation data for all TCs over the box centered on the storm. We will put the capital-letter marked gridded regions as the focus of the present study. In order to understand the relationship between the spatial precipitation distribution and intensity change of the landfalling TCs, all named TCs that formed in the western North Pacific during the period 2000–2009 are grouped into weakening and intensifying TCs based on the 24-h intensity change in the maximum sustained wind speed.

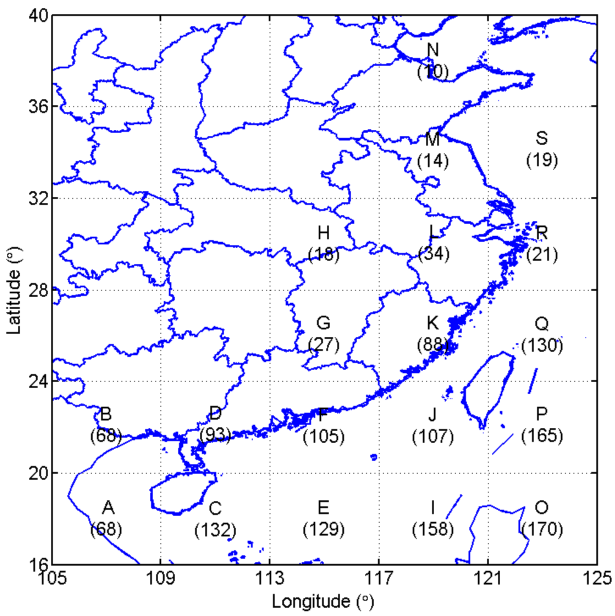


Figure 1. The study area and each of the 4°×4° boxes. The numbers in the parenthesis denote the frequency of occurrences for landfalling TCs in each box.

3 SPATIAL DISTRIBUTION OF PRECIPITATION FOR LANDFALLING TCS AFFECTING CHINA

To investigate the detailed distribution of precipitation for landfalling TCs affecting China, the composite precipitation fields for each of the boxes are demonstrated in Figure 2. For boxes A, B, C, D, E, F, and I, the precipitation distribution features are very similar to that in box E shown in Figure 2a, with a precipitation maximum to the south-west quadrant of the TC in both the storm core (defined as the inner 100 km, the same below) and the outer-band region (*r*=100-200 km, the same below) prior to, during and after the landfall of TC across the south China coast. This type of precipitation distribution over boxes A, B, C, D, E, F, and I is classified as South-West Type in this paper, with landfalling TCs affecting the south China coast and South China Sea. For boxes J, O, P, and Q, the precipitation distribution features are very similar to that in box P shown in Figure 2b, with a strong preference for maximum rainfall in the southern quadrants in the storm core region, while there is a nearly symmetrical precipitation in all quadrants in the outer rainbands prior to, during and after the landfall. This type of precipitation distribution over boxes J, O, P, and Q is classified as Symmetrical South Type in this paper, with landfalling TCs affecting the northern South China Sea and middle-west part of the western North Pacific. The third type of precipitation distribution is called South Type in this paper, with a strong preference for main rainfall in the south quadrants shown in Figure 2c. This type of precipitation distribution over boxes G, H, K, L, and R are related to landfalling TCs affecting the east China coast and eastern provinces of China. The North Type is the fourth type of precipitation distribution with a strong preference for main rainfall in the north quadrants shown in Figure 2d. This type of precipitation distribution over boxes M, N, and S are related to landfalling TCs across the Yellow Sea and the Bohai Sea. The four types of precipitation distributions are shown in Figure 2e.

4 RELATIONSHIPS BETWEEN PRECIPITATION DISTRIBUTION AND INTENSITY OF LANDFALLING TCS

To demonstrate the generality of the results and to explore some of the differences between intensifying and weakening TCs, a composite of the precipitation distribution of landfalling TCs with different intensity is further examined. After sorting all TCs into weakening, neutral (no-change) and intensifying groups according their 24-h intensity changes in the maximum sustained wind speed, we select the intensifying and weakening cases to discuss the relationship between the precipitation distribution and the TC intensity. In the current study, we analyzed the features of the spatial distribution of precipitation associated with landfalling TCs from three aspects: the maximum precipitation, the precipitation coverage area and the distance from the center of the torrential rain (defined as the precipitation of more than 100 mm in 24 h, which equals to a precipitation rate of 4.17 mm/h, the same below) to the center of TC.

Figure 3 shows the relationships between the maximum precipitation (Pmax) and the intensity of the landfalling TCs. It can be seen from Figure 3a that for the intensifying TCs, the maximum precipitation increases with the increase of TC intensity over boxes J and M, while decreasing with the increase of TC intensity over boxes A, B, and R regions. But for the weakening TCs (Figure 3b), the maximum precipitation increases with the increase of TC intensity across the south China coast, the Philippine Islands coast as well as the southeast coast of Taiwan Island (boxes D, F, I, L, O, and P).

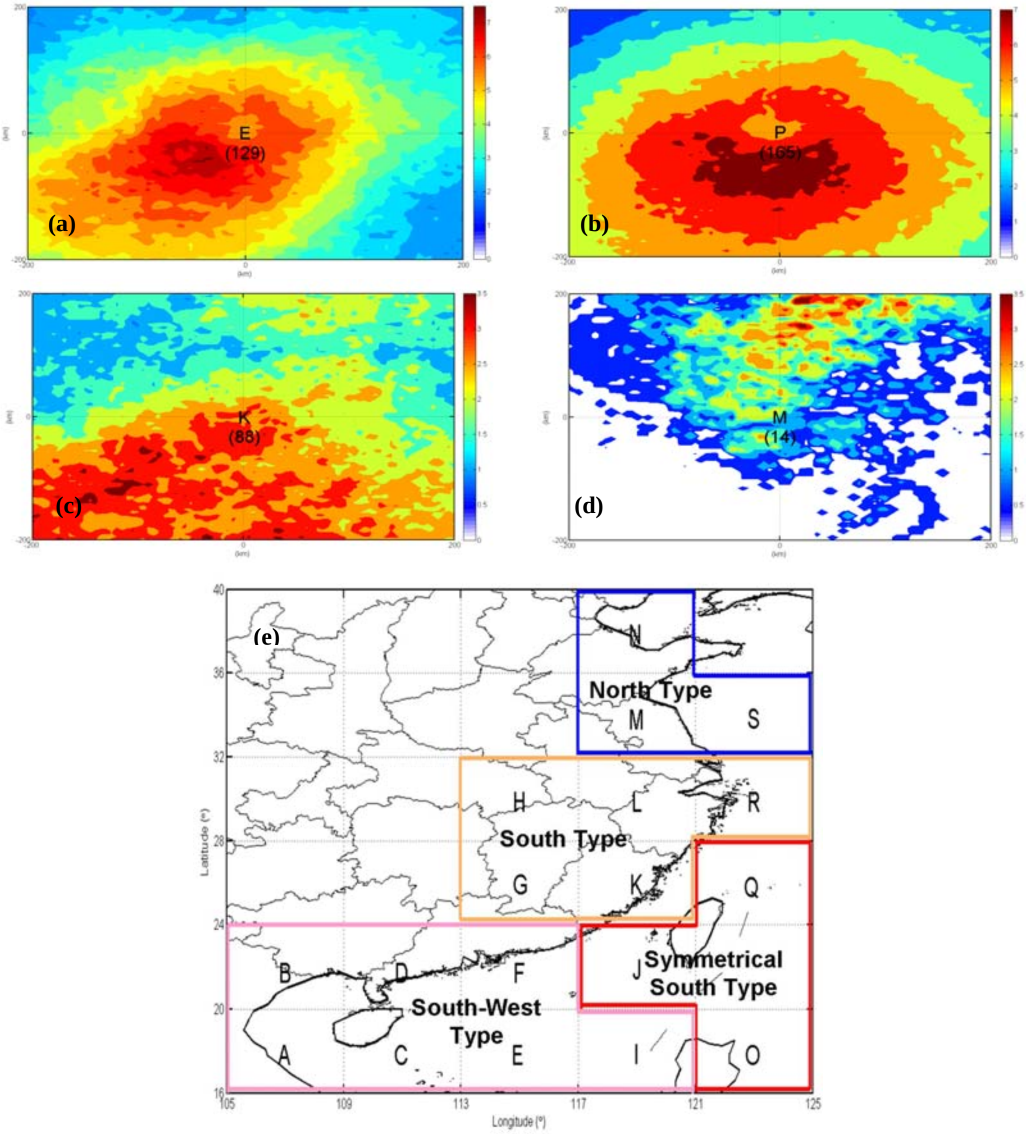
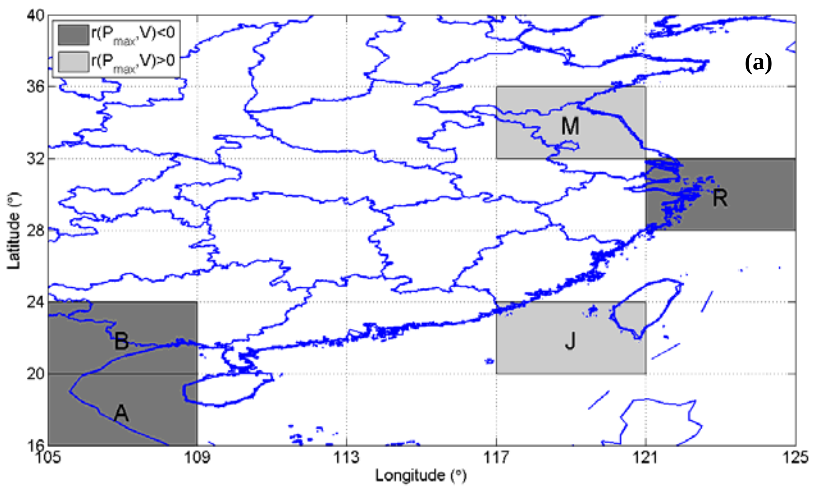


Figure 2. Four types of common spatial distributions of precipitation associated with landfalling TCs affecting China. (a) South-West Type, (b) Symmetrical South Type, (c) South Type, (d) North Type, and (e) four types of distribution of precipitation across the coastal regions of China. The numbers in the parenthesis denote the frequency of occurrences for landfalling TCs in that box.



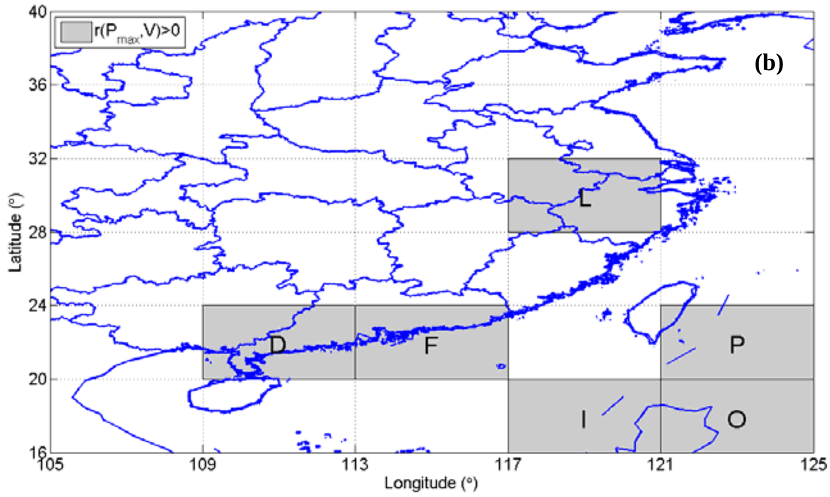
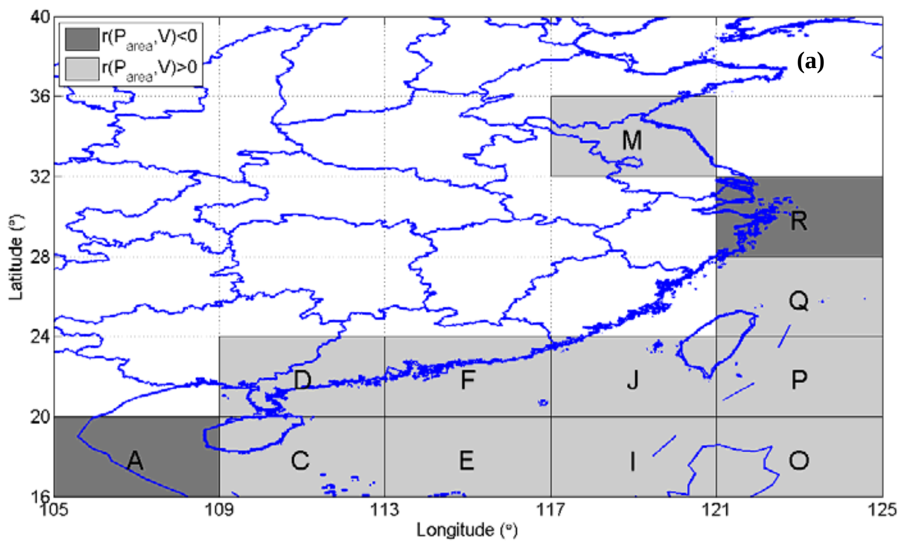


Figure 3. The relationships between the maximum precipitations (Pmax) and the intensity of the landfalling TCs (V) for (a) intensifying TCs and (b) weakening TCs. The positive and the negative correlation coefficients (*r*(Pmax, V)) which are significant at the 95% level indicate the maximum precipitation increases and decreases with the increase of TC intensity, respectively.

Figure 4 shows the relationships between the precipitation coverage area (Parea) and the intensity of the landfalling TCs. It can be seen that the precipitation coverage area (Parea) is significantly correlated with the intensity of the landfalling TCs over most of the regions. An additional feature seen in Figure 4 is that as the TC intensity increases, the associated precipitation covers larger area for both intensifying and weakening TCs around landfall. But over individual regions (A and R), the precipitation coverage area related to landfalling TCs decreases with the increase of the intensifying TC intensity.

The combined results of Figures 3 and 4 clearly indicate that for the intensifying TCs, both the maximum and the coverage area of the precipitation associated with the landfalling TCs increase with the increase of the TC intensity over regions J and M, while decreasing over regions A and R. But for the weakening TCs, the positive relation between the maximum precipitation and the precipitation coverage area and TC intensity exists over most regions (D, F, I, O, P, and L).

Another aspect of the precipitation distribution features associated with landfalling TCs is the position of the center of the torrential rain relative to the TC center. From Figure 5, it can be seen that for both the intensifying and weakening TCs, the correlations between the distances from the center of the torrential rain to the TC center and the TC intensity is mostly negative, indicating that the center of torrential rain in TC shifts toward the TC center as the intensity of TC increases. This result is consistent with recent observational analyses of Chen et al.[19] and many of other numerical studies.



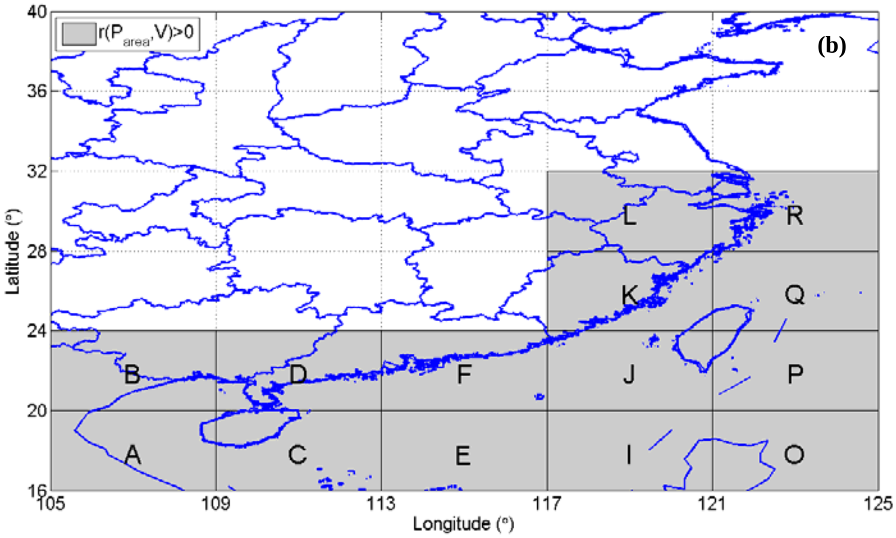


Figure 4. The relationships between the precipitation area (Parea) and the intensity of the landfalling TCs (V) for (a) the intensifying TCs and (b) the weakening TCs. The positive and the negative correlation coefficient (*r*(Parea, V)) indicates that the precipitation area increases and decreases with the increase of TC intensity, respectively.

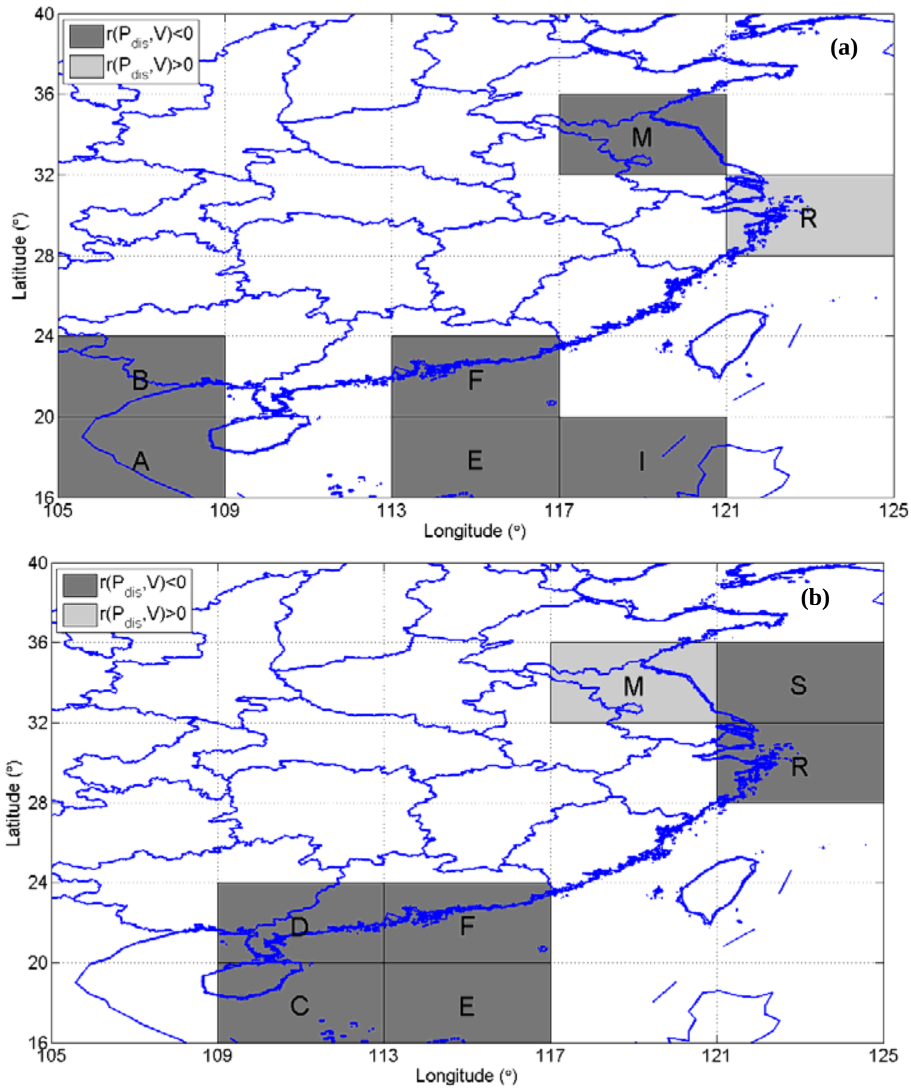


Figure 5. The relationships between the distance from the center of the torrential rain to the center of TC (Pdis) and the intensity of the landfalling TCs (V) for (a) the intensifying TCs and (b) the weakening TCs. The positive and the negative correlation coefficient (*r*(Pdis, V)) indicates that the distance from the center of the torrential rain to the center of TC increases and decreases with the increase of TC intensity, respectively.

5 POSSIBLE CAUSE OF THE ASYMMETRIC PRECIPITATION DISTRIBUTION

Observational and numerical studies suggested that stronger convection is generally found in the front quadrant of the TC core relative to the storm motion with a slight preference for the right-front quadrant. For example, Parrish et al.[10] found left-front quadrant maxima in precipitation in Hurricane Frederick (1979). Shapiro[20] found that convergence was more significant ahead of a slow-moving storm (< 5 m s^{-1}) but more concentrated on the right-front quadrant for a fast-moving storm (> 10 m s^{-1}). A recent observational study by Corbosiero and Molinari[13] showed a maximum number of lightning flashes in the front quadrants, with a slight preference for the right-front quadrant, in the inner core (r < 100 km), based on the lighting distributions in 35 Atlantic hurricanes from 1985 to 1999.

Previous observational and numerical studies suggested that vertical wind shear has a significant effect on the convective distribution in TCs. An observational study of Corbosiero and Molinari[21] showed a strong preference for ground flashes in the downshear quadrant in the inner core, which is more significant for storms under a strong vertical shear. Black et al.[22] examined the impact of vertical shear on the convective structure of Hurricanes Jimena and Olivia over the eastern Pacific based on airborne radar data. They showed a strong wavenumber-1 component of radar reflectivity with highest reflectivity on the left side of the shear vector. Rogers et al.[12] investigated the influence of vertical wind shear on the azimuthal distribution of rainfall in Hurricane Bonnie (1998) based on numerical simulation and found a significant relation between the distribution of model-derived reflectivity and the magnitude and direction of the vertical wind shear. Stronger convection is found on the left side of the shear vector if the shear is strong while the distribution of reflectivity is more symmetric if the shear is weak. Recent observational work by Chen et al.[19] showed that the vertical wind shear is a dominant factor for the downshear left rainfall asymmetry when shear is > 5 m s^{-1} and TC translation speed becomes an important factor in the low shear (< 5 m s^{-1}) environment.

In order to study the influences of storm motion and the environmental vertical wind shear on rainfall asymmetries in the TC core, two types of distribution of precipitation relative to storm motion, the South-West Type and the Symmetrical South Type as in Figure 2e, and vertical wind shear are examined, since the significant asymmetries in heavy rainfall distribution mainly occur in these two types. The mean environmental vertical wind shear for the South-West Type is about 12 m s^{-1} and from the north-northeast direction (Figure 6a), with the storm tracks being west-northwestward. The rainfall in the TC core appears stronger in the southwest quadrant, indicating that the vertical wind shear largely contributes to the asymmetric convective distribution with stronger precipitation in the downshear sector, especially during landfall (when the center of TC is located in boxes A, B, C, D, F, and I). However, the mean vertical wind shear is about 9 m s^{-1} and basically from the east (Figure 6b), which is nearly opposite to the direction of storm motion, and strong convection is almost absent in the southern sector when TC is weakening and situated at the region of box E. The stronger convection located downstream and left of the shear vector is well consistent with the results from previous studies[13-15, 23]. Also, for the Symmetrical South Type, the southern precipitation asymmetry in the inner region is predominantly attributed to the effect of the strong southwest-direction vertical wind shear (Figure 6c). Considering the strong vertical wind shear environment experienced by landfalling TCs across the south and east China coasts (Figure 6), the present findings are in good agreement with recent observational analyses of Chen et al.[19], who suggested that the vertical wind shear is a dominant factor for the rainfall asymmetry when shear is > 5 m s^{-1} and TC translation speed becomes an important factor only in the low-shear environment.

6 SUMMARY AND CONCLUSIONS

This study examined the spatial distribution of precipitation associated with landfalling tropical cyclones (TCs) affecting China based on the GMS5-TBB retrievals. All named TCs that formed over the western North Pacific and made direct landfall over China during the period 2001–2009 are included in this study. Based on the 24-h intensity changes of these TCs, all selected cases are categorized into intensifying, neutral and weakening cases in each of the 4°×4° boxes. The relationships between precipitation distributions and intensity of landfalling TCs are further investigated to provide an operational reference for TC precipitation forecast.

Results show that there are four main types of distribution of precipitation associated with landfalling TCs affecting China, which are the South-West Type, with a precipitation maximum to the southwestern quadrant of TC; the Symmetrical South Type, with the rainfall being more pronounced to the south sides of TC in the inner core and a symmetrical rainfall distribution in the outer band region; the South Type, with the rainfall maxima being more pronounced to the south of TC, and the North Type, with the rainfall maxima being more pronounced to the north of TC. The landfalling TCs, with different types of distribution of precipitation, affect different coastal regions of China. For the intensifying TCs, both the maximum and coverage area of the precipitation associated with the landfalling TCs increase with the increase of TC intensity over northern Jiangsu province and southern Taiwan Strait (boxes J and M), while decreasing over Beibu Gulf and the sea area of Changjiang River estuary (boxes A and R). But for the weakening TCs, positive relation between the maximum precipitation and the precipitation coverage area and TC intensity exists over most regions (D, F, I, O, P, and L). For all TCs, the center of the torrential rain in TC shifts toward the TC center as the intensity of TC increases. This finding is consistent with many previous studies.

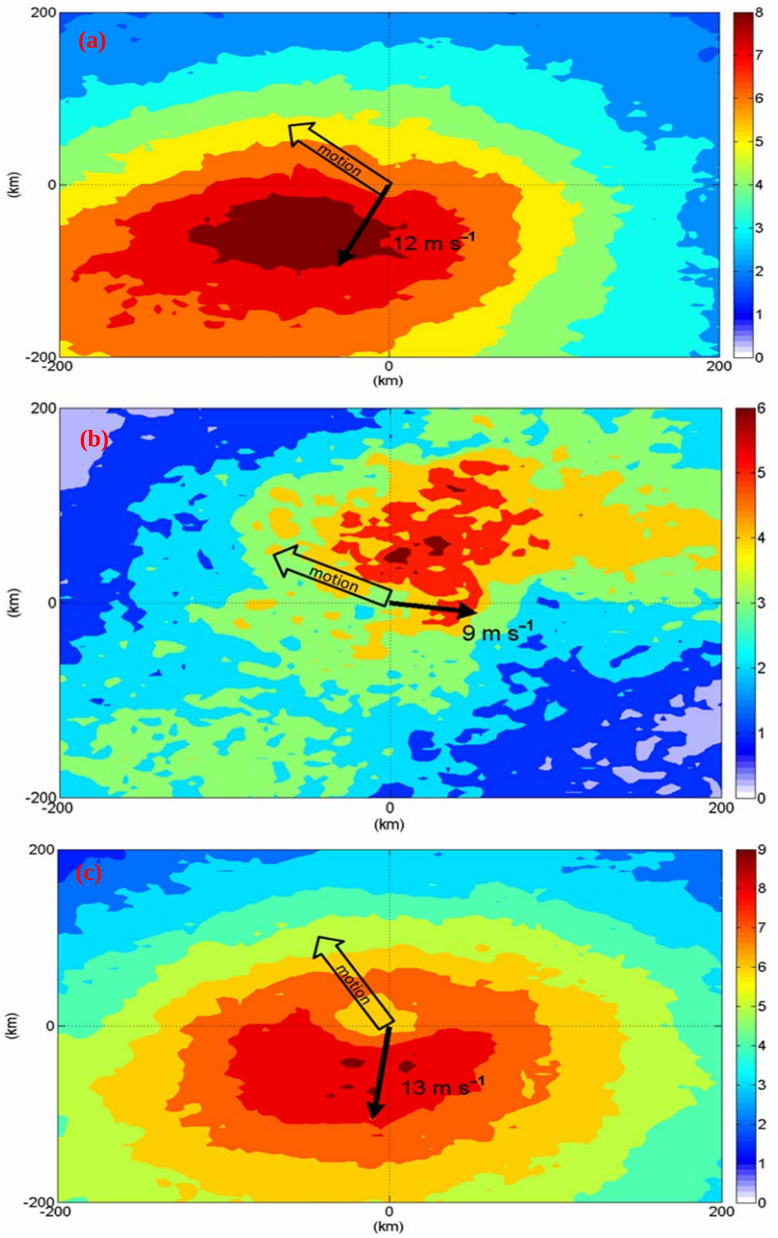


Figure 6. The mean storm motion and the mean 200-850 hPa vertical wind shear for (a) South-West Type, (b) weakening TCs whose centers are located in box E, and (c) Symmetrical South Type. The solid arrows indicate the mean environmental wind shear crossing the storm core of radius 800 km, and the open arrows represent the mean storm motion.

The possible causes of the asymmetric rainfall in landfalling TCs, which mainly occurred in South-West Type and Symmetrical South Type, are also discussed in this paper. Results show that the environmental vertical wind shear mainly contributes to the stronger rainfall in the downshear quadrants, especially during landfall. The result is also consistent with previous studies.

Although such observations have been made in the Atlantic basin, whether this is a general phenomenon applicable to all landfalling TCs or a specific feature of the Chinese coast needs to be investigated further with a larger sample size and more numerical studies.

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