Rainfall asymmetries of the western North Pacific tropical cyclones as inferred from GPM

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Abstract
It has been revealed that the vertical wind shear (VWS) can result in the rainfall asymmetry of tropical cyclone (TC), where the VWS is conventionally defined as the environmental horizontal winds between 200- and 850-hPa levels within a certain area from the TC centre. The rainfall maximum is generally displaced downshear to downshear-left side in the Northern Hemisphere or downshear to downshear-right side in the Southern Hemisphere. Here, we revisit the rainfall asymmetries of TCs over the western North Pacific using the state-of-art Global Precipitation Measurement data. Observations pose that using the conventional VWS to interpret the TC rainfall asymmetry is inappropriate. The conventional VWS can only largely grasp the rainfall asymmetry in the inner core of TC, but not in the outer core. We, therefore, explicitly propose a new VWS, namely the effective VWS, to fill this gap. The effective shear layer responsible for the rainfall asymmetry is a function of TC intensity and core region. In addition, we suggest that the angle difference between the effective shears for the inner-core and outer-core rainfall asymmetries can help to comprehend the spirality of the rainfall asymmetries that are, the fashions, or patterns of the rainbands. Meanwhile, the moisture flux convergence and storm motion show little effect on the rainfall asymmetry. This study advances the understanding of TC rainfall asymmetry and provides scientific support for disaster prediction, prevention, and mitigation.

KEYWORDS
effective vertical wind shear, GPM, moisture flux convergence, rainfall asymmetry, tropical cyclone, tropical cyclone motion

1 | INTRODUCTION

The strong winds, heavy rain, and storm surges brought by a tropical cyclone (TC) can cause various degrees of impacts, among which heavy rain can arouse a series of disasters such as floods, urban water logging, mudslides, landslides, and so forth, that could lead to huge economic losses and casualties. Understanding the distribution and intensity of TC rainfall has, therefore, always been a topic of great interest and research. Many observational
studies, based on radar, lightning, reanalysis, and satellite-derived data, have shown that TCs not only possess significant rainfall or convective activity asymmetries over oceans (e.g., Burpee and Black, 1989; Corbosiero and Molinari, 2002, 2003; Cecil, 2007; Cao et al., 2016; Gao et al., 2018; Kim et al., 2018; Pei and Jiang, 2018), but also prior to, during and after landfalls (e.g., Liu et al., 2007; Xu et al., 2014; Yu et al., 2015; Chan et al., 2019; Wen et al., 2019). Meanwhile, a lot of numerical studies have also been carried out to examined the possible factors and mechanisms responsible for the TC rainfall asymmetry (e.g., Jones, 1995; Frank and Ritchie, 1999, 2001; Rogers et al., 2003; Lonfat et al., 2007; Molinari, 2002, 2003; Cecil, 2007; Cao et al., 2007). Previous studies basically investigated the relationships of TC rainfall asymmetry with either the vertical wind shear (VWS; e.g., Kim et al., 2019), TC motion (e.g., Chen et al., 2006), water vapour flux (e.g., Rodgers et al., 1994), or topography (e.g., Chan et al., 2004). They all agree that the VWS is the predominant factor that causes the rainfall asymmetry, while others are comparatively not apparent. The VWS is conventionally defined as the environmental horizontal winds between 200- and 850-hPa levels within a certain area from the TC centre. The maximum rainfall is generally observed on the downshear to, more likely, downshear-left side in the Northern Hemisphere or downshear to, more likely, downshear-right side in the Southern Hemisphere, regardless of the shear orientation, TC motion and topography. What is more, higher rainfall asymmetry is found to be associated with stronger VWS (Marks, 1985; Wang and Holland, 1996; Wingo and Cecil, 2010).

Strictly speaking, however, the conventional VWS cannot explain the TC rainfall asymmetry comprehensively. As will be shown and discussed in this study, the conventional VWS can only largely grasp the rainfall asymmetry in the inner core of TC, but not in the outer core. Besides, previous studies mainly examined the shear-relative rainfall and motion-relative rainfall, while the moisture flux convergence (MFC) relative rainfall, which could be indicative to the rainfall asymmetry, receives limited attention (Gao et al., 2012; Gao et al., 2018). In addition, the tropical rainfall measuring mission (TRMM) data that were mainly used to estimate the TC rainfall in previous studies are out-of-date. The state-of-art global precipitation measurement (GPM) data building upon the success of the TRMM provide more accurate and informative rainfall estimates in a higher spatiotemporal resolution ever (see Section 2.2). Therefore, this study aims to advance the understanding of TC rainfall asymmetries by examining the shear-relative and MFC-relative rainfall in both the inner core and outer core of TCs, particularly the TCs over the western North Pacific, using the GPM data, improving the forecast skill of TC rainfall ultimately. The relative importance of the motion-relative rainfall will also be discussed.

2 | DATA AND METHODOLOGY

2.1 | Best-track data

To be in line with the data coverage of GPM (see Section 2.2), the 6-hr best track data including the positions and 1-min maximum sustained winds of TCs over the western North Pacific in 2014–2018 are retrieved from the Joint Typhoon Warning Center (JTWC). There are 126 TCs in total. According to their instantaneous intensity, they are stratified into four categories: (a) Tropical Depression (TD) or below; (b) between Tropical Storm (TS) and Severe Tropical Storm (STS); (c) between Typhoon (TY) and Severe Typhoon (STY); and (d) Super Typhoon (SuperT) or above. The corresponding intensity ranges are specified in Table 1. The hourly best-track data are estimated by the linear interpolation whenever it is applicable.

2.2 | GPM data

The integrated multi-satellite retrievals for global precipitation measurement (GPM) (IMERG) data in 2014–2018 are used as the observations for the evaluation of TC rainfall. The GPM Core Observatory initiated by the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA) was launched on February 27, 2014. The temporal and spatial resolutions are 30-min and 0.1° × 0.1° (in the latitude range from 60°S to 60°N), respectively. The IMERG is the Level 3 multi-satellite precipitation algorithm of GPM, which combines intermittent precipitation estimates from all constellation microwave sensors (Huffman et al., 2012; Chen et al., 2018). It is the state-of-art satellite-derived precipitation data building upon the success of the TRMM, in which the temporal and spatial resolutions of TRMM are coarser (3-hr and 0.25° × 0.25° in the latitude range from 50°S to 50°N, respectively). The GPM mission provides a new generation of rain and snow data products in all parts of the world within 3 hr. It has more accurate instantaneous precipitation measurement, especially for light rain and cold-season solid precipitation and unified precipitation retrievals from all constellation radiometers using a common observationally constrained global hydrometeor database (Hou et al., 2013).

In this study, the area around each storm is divided into two regions: the inner 150 km, hereafter referred to as the inner core, and the annulus encompassed by the 150–300-km radii, referred to as the outer core. The locations of
Effective shear layers responsible for the inner-core and outer-core TC rainfall asymmetries and the corresponding numbers of samples for the TCs at different TC intensity and in different core regions

| $V_{\text{max}}$ (kt) | Shear top (hPa) | Shear base (hPa) | Samples | Effective shear for the inner core rainfall asymmetry ($S_i$) |
|--------------------------|-----------------|-----------------|---------|---------------------------------------------------------|
| TD                       | <34             | 300             | 850     | 276 (13.56%)                                            |
| TS–STS                   | 34–63           | 300             | 850     | 482 (41.36%)                                            |
| TY–STY                   | 64–99           | 200             | 850     | 611 (30.01%)                                            |
| SuperT                   | $\geq$100       | 200             | 850     | 307 (15.07%)                                            |
| Total                    |                 |                 |         | 2036 (100%)                                             |

| Shear top (hPa) | Shear base (hPa) | Samples |
|-----------------|-----------------|---------|
| 400             | 850             | 339 (16.87%) |
| 400             | 925             | 527 (26.23%) |
| 300             | 925             | 275 (13.69%) |

The vertical wind shear (VWS) is defined as the environmental horizontal winds between the shear layer top and bottom, respectively. These values are set to maximize the number of samples where precluding those samples in which the rainfall rates are too weak for a meaningful estimate of the area of maximum rainfall activity. Incorporating with the 6-hr best-track data, there are totally 2036 and 2009 instantaneous observations in the inner-core and outer-core regions, respectively. The sample sizes are statistically large enough for accomplishing this study (Table 1).

### 2.3 ERA5 data

The hourly and 0.25° × 0.25° fifth generation of European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalyses of the global climate (ERA5) data set including the pressure, winds and humidity in 2014–2018 are extracted to examine the contributions of the VWS and MFC to the TC rainfall asymmetry. The ERA5 is the latest generation of ECMWF global atmospheric reanalysis which provides hourly reanalyses of many atmospheric, land and oceanic climate variables. It is one of the mainstreams of the existing reanalyses. Data cover the Earth on a 30-km grid and resolve the atmosphere using 137 levels from the surface up to a height of 80 km.

### 2.4 VWS

The vertical wind shear (VWS) is defined as the environmental horizontal winds between the shear layer top and base within 600-km radius from the TC centre. The shear layer tops are set to be 100, 200, 300, 400, 500, 600, and 700 hPa, while the shear layer bases are 400, 500, 600, 700, 800, 850, 925, and 1,000 hPa. Thence, there are 28 shear layers in total (100–400, 100–500, 100–600, 100–700, 100–850, 100–925, 100–1,000, 200–500, 200–600, 200–700, 200–850, 200–925, 200–1,000, 300–600, 300–700, 300–850, 300–925, 300–1,000, 400–700, 400–850, 400–925, 400–1,000, 500–850, 500–925, 500–1,000, 600–925, 600–1,000, and 700–1,000 hPa; see Figures 1 and 3).

The VWS is further divided into four categories to examine the effects of the magnitude of the VWS on the distribution of TC rainfall. Weak shear is defined as a shear below 5 m s\(^{-1}\), moderate shear between 5 and 10 m s\(^{-1}\), strong shear between 10 and 15 m s\(^{-1}\), and very strong shear greater than 15 m s\(^{-1}\).

### 2.5 MFC

The moisture flux convergence (MFC) is a term in the conservation of water vapour equation. It is a measure of the degree to which moist air is converging into a given area, taking into account the effect of converging winds and moisture advection. The vertically integrated MFC is highly correlated with the frontal and convective activity, and thus, is indicative to the rainfall associated with the synoptic-scale systems (Banacos and Schultz, 2005; Zomeren and Delden, 2007). The vertically integrated MFC is calculated as:

$$
\text{MFC} = -\frac{1}{g} \nabla \cdot \left( \int_{P_T}^{P_S} q V dp \right)
$$

where $q$ is specific humidity, $V$ is horizontal wind vector, $g$ is acceleration of gravity, $P$ is pressure, $P_S$ is surface pressure, and $P_T$ denotes pressure for the upper bound, which is 100 hPa in this study.

For the ease of examining the MFC effects on TC rainfall asymmetry, the MFC is vectorized and is defined

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as the vector pointing from the TC centre to the area of the maximum MFC in a particular region. $\mathbf{M}_i$ and $\mathbf{M}_o$ are the MFC vectors in the inner-core and outer-core regions, respectively.

3 | RESULTS

Consistent with previous studies, the maximum rainfall is generally found on the downshear quadrants, in particular of the downshear left, in the inner core (Figure 1). The well-interpreted mechanism behind is that different vertical levels of TC experience differential advection and the vortex tilts in response to VWS (e.g., Jones, 1995; Frank and Ritchie, 1999). The mutual corotation of the vortices at different levels causes the direction of tilt to rotate cyclonically from the shear vector. The direction of tilt results in asymmetric vertical motion such that the rainfall is typically displaced downshear to, more likely, downshear-left side in the Northern Hemisphere or downshear to, more likely, downshear-right side in the Southern Hemisphere (e.g., Kim et al., 2018). In this study, the largest proportions of the maximum rainfall on the downshear-left side of the TCs at TD, TS–STS, TY–STY, and SuperT intensity (shading; unit: %) as a function of the shear layer. Shear layer tops and shear layer bases are denoted by the blue and brown solid lines, respectively (unit: hPa). Quadrants DL, DR, UL, and UR stand for downshear-left, downshear-right, upshear-left, and upshear-right, respectively. The largest proportion of the maximum rainfall on DL in each TC intensity category is indicated by the vertical dashed line.
convection could be attained (Figure 2). The deeper convection suggests that the deeper shear layer would take effect on it, and thus, the corresponding effective shear layer top is higher.

In the outer core, the maximum rainfall is generally found on the downshear to, particularly, downshear left too (Figure 3). The largest proportions of the maximum rainfall on the downshear left of the TCs at TD, TS–STS, TY–STY, and SuperT intensity account for 58.4, 65.4, 57.1, and 54.6%, respectively. Such the high proportions suggest that the aforementioned mechanism in the inner core also applies in the outer core. However, the corresponding shear layers differ from those found in the inner core. They are 400–850, 400–850, 400–925, and 300–925 hPa, respectively. Similar to what has performed in the inner core, henceforth, we define them as the effective shear layers for the outer-core rainfall asymmetry. It is noted that these effective shear layer tops also tend to increase with TC intensity. This agrees with Figure 2 that the mean upward motion in the outer core increases with TC intensity. Stronger upward motion suggests deeper convection, and thus, the higher effective

**FIGURE 2** Vertical velocity averaged from the surface to 200 hPa of the TCs at (a) TD, (b) TS–STS, (c) TY–STY and (d) SuperT intensity (unit: Pa s$^{-1}$). Negative values mean upward motions. Inner ring and outer ring indicate the radii of 150 and 300 km from the TC centre, respectively, where TC centre is at the intersection of two dashed lines.
shear layer top is expected. However, remarkably, none of these effective shear layers pertains to the conventional shear layer (200–850 hPa). The effective shear layer tops in the outer core are all lower than those in the inner core (cf. Figures 1 and 3). It is because the outer core does not embody eyewall, where the upward motion is the strongest, the mean upward motion (Figure 2), and hence, the mean depth of convection in the outer core are therefore considerably lower than that in the inner core. Therefore, considering the differential advection on top of the convection is no longer physical for comprehending the rainfall distribution. This could be the reason why the conventional VWS can largely grasp the rainfall asymmetry in the inner core, but not in the outer core. Meanwhile, the effective shear layer bases for the outer-core rainfall asymmetry of TCs at TY intensity or above are found to be a bit lower than those for the inner core, but the reason for this is not clear.

It is noteworthy that in the outer-core region of TCs at TD intensity or below, there are layers of VWS for which the convection in the other quadrants are comparable or even larger than that in the downshear-left quadrant (Figure 2a). This makes sense because for a weak TC, its convection is not well-developed and well-organized in the outer core. Thus, other factors like warm ocean eddies and synoptic moisture could contribute to the rainfall asymmetry significantly. A series of case study would be required for further examination, which is out of scope of the current composite study. Nonetheless, the TCs at TD intensity or below are typically not the focus in the perspective of TC rainfall, while those at TS or above receive more attention because latter possess stronger convection, and thus, considerable rainfall.

Table 1 summarizes the effective shear layers responsible for the rainfall asymmetries of TCs at different TC intensity and in different core regions. It is proposed that the effective shear layer comprehending the TC rainfall asymmetry is a function of TC intensity and core region. Besides, Figure 4a shows that the preference of maximum rainfall on the downshear to downshear-left side (−90 to 30° relative to the effective shear vectors) is evidently strong. There are 70.7 and 70.6% of the maximum rainfall in the inner core and outer core, respectively.

In addition to the effective VWS, the MFC is examined if it could be another significant factor that can contribute to the distribution of TC rainfall. Figure 4b shows that the rainfall maxima are generally found on the front

![Figure 3](image-url) 

**Figure 3** As in Figure 1, but in the outer core (150–300 km) of the TCs
side of the MFC vectors (account for 41–42% on the regions between −60° and +30° relative to the MFC vectors). However, comparing to the effective shear-relative rainfall asymmetries, those of the MFC-relative are more scattered (cf. Figures 4a,b).

Figure 5 shows the distributions of the heading directions of the effective VWS and MFC vectors. The TCs over the western North Pacific largely experience the easterly and northeasterly shears, which is consistent with previous studies (Li, 2006; Lin et al., 2010). Results suggest that the TCs at STS intensity or below likely experience easterly shear (Figure 5a,b), while those at TY intensity or above likely experience northeasterly shear (Figure 5c,d). The absolute easterly shear shows a strong negative correlation with the number of TCs suggesting that a decrease in easterly shear is favourable for the formation of more storms (Rao et al., 2008). The preferences of westerly or southwesterly shears are also observed, but relatively less prevailing. Yet, the directions of MFC vectors demonstrate higher variability. No apparent orientation preference is found, but they are likely heading to the downshear side.

In order to study the relative importance of the effective VWS and MFC to the TC rainfall asymmetries, the distributions of TC maximum rainfall for different angles of separation between the effective VWS and MFC are examined (Figure 6). Results show that the samples are largest when the angles of separation between effective VWS and MFC are small. This suggests that the effective VWS and MFC often overlap or deviate a bit with each other, which agrees with what has concluded in Figure 5. In addition, Figure 6 demonstrates that the contribution of MFC to the distributions of TC rainfall maxima is negligible. These together imply that the rainfall maxima generally found on the front side of the MFC vectors are likely in response to the effective VWS. The locations of rainfall maxima are predominantly determined by the effective VWS such that maximum rainfall is typically situated on the downshear to, particularly, downshear-left side. In view of this, we focus on the effective VWS hereafter.

The distributions of maximum rainfall at different intensity are further examined by stratifying the samples into different VWS intensity categories (Figure 7). Results show that most samples are under the weak and moderate shears. This is well-understood because the weak-to-moderate shear is one of the environmental conditions favourable to tropical cyclogenesis and development. Secondly, it is found that the rainfall maxima are primarily located on the downshear to downshear-left side (−90 to 30° relative to the effective shear vectors) in both the inner and outer cores of TCs. The proportions account for 50–100% in the inner core and 60–100% in the outer core. Thirdly, results suggest that the stronger effective VWS does not only result in higher rainfall asymmetry in the inner core of TC (DeMaria, 1996), but also in the...
outer core. The proportion of samples on the downshear-left side increases with effective VWS. Lastly, it is observed that the distributions of rainfall maxima are more scattered for the TCs at higher intensity. The deviations of the proportions of the rainfall maximum distribution among the sectors or segments are generally smaller for the TCs at higher intensity (cf. first and last rows in Figure 7). Such observations agree well with the concept of the inertial stability of TC. A TC at higher intensity possesses higher inertial stability. A vortex
FIGURE 6  Distributions of the TC rainfall maxima for different angles of separation between the effective shear (S) and MFC (M) vectors (each ±15°, indicated by semi-transparent blue sectors). Inner disc and outer ring show the sample distributions in the inner-core and outer-core regions, respectively. The areas larger than 9% are shaded, in which those having darker shadings indicate they possess larger proportions.
having high inertial stability would resist perturbations and environmental influences, like the VWS, and would remain rather symmetric. A low inertial stability vortex, on the other hand, is more readily influenced by outside disturbances, and would be less symmetric.

Last but not least, this study remarkably shows that the direction of the effective shear for the outer-core rainfall asymmetry ($S_o$) does not always align with that for the inner core ($S_i$). They appear to have a slight deviation preference between each other (see Figure 5).

Figure 8 depicts the distributions of angle differences between $S_i$ and $S_o$ ($S_i$ minus $S_o$) for TCs at different intensity. The maximum rainfall in the inner core is generally observed $0\rightarrow 40^\circ$ cyclonically ahead of that in the outer core (i.e., $-40$ to $0^\circ$ in Figure 8). Taking all samples as a whole, about 53% of samples are in such configuration, while 23% are found in the situation that the maximum rainfall in the inner core is $0\rightarrow 20^\circ$ cyclonically behind that in the outer core (i.e., $0\rightarrow 20^\circ$ in Figure 8).
Figure 9 shows an in-depth examination of the distributions of TC rainfall maxima for different angles of separation between \( S_i \) and \( S_o \). Consistent with Figure 8, it is often that the \( S_i \) is slightly cyclonically-ahead of or aligned with \( S_o \) (Figure 9a,b), in which the sample sizes are largest. The rainfall asymmetries in both the inner-core and outer-core regions match well with the corresponding \( S_i \) and \( S_o \) such that the rainfall maxima are generally displaced downshear to downshear-left side. Specifically, Figure 9a,b depict an outward propagation of the heaviest rainfall in a spiral fashion, which agrees with many typical observations. The rainfall maxima in the inner and outer cores likely come from the same rainband (e.g., STS Matmo [2014] in Figure 9e), though coming from multiple rainbands (e.g., SuperT Hagupit [2014] in Figure 9d) is plausible but relatively less likely. The fashions and proportions of the maximum rainfall distributions suggest that the larger the angle difference between the \( S_i \) and \( S_o \) could lead to the higher spirality of rainband. On the other hand, when the \( S_i \) is cyclonically-behind the \( S_o \), the outer-core rainfall maximum is ahead of the inner-core rainfall maximum in general (Figure 9c). In this circumstance, the rainfall maxima in the inner and outer cores likely originate from multiple rainbands (e.g., STY Lionrock [2016] in Figure 9f), though originate from the same rainband is possible but relatively less likely (Gao et al., 2020).

These results give observational and physical insights into the understanding of the spirality of TC rainfall asymmetries, that are, the fashions or patterns of the rainbands. What is more, it is noteworthy that with the advancement of spatiotemporal resolution of GPM, it allows us to perform these subtle analyses by partitioning the domain of interest into two regions (inner core and outer core) and 12 sectors or segments each, whereas the previous studies are mostly conducted by dividing the whole into one or two region(s) and four quadrants or eight sectors each (e.g., Corbosiero and Molinari, 2003; Chen et al., 2006; Ueno, 2007). According to our best knowledge and comprehensive literature review, this study is the leading edge that reveals such meticulous features.

4 | DISCUSSION AND SUMMARY

Some studies (e.g., Corbosiero and Molinari, 2003; Chen et al., 2006) suggest that the motion or translation speed of TC could contribute to the rainfall asymmetry, particularly when the VWS is weak. To examine the relative importance between the effective shear and TC motion on the rainfall asymmetry, the motion-relative rainfall in both the inner core and outer core of TCs are performed. Figure 10 clearly show that the effective shear still plays the dominant role under the weak shear environment even the TCs are translating fast (translation speed \( >5 \, \text{m} \cdot \text{s}^{-1} \)). The maximum rainfall largely appears on the down-effective-shear-left side. The same conclusion can also be drawn from the slow-moving TCs (translation speed \( \leq 5 \, \text{m} \cdot \text{s}^{-1} \); not shown). These results demonstrate the high generality and potential of the use of effective shear in determining the TC rainfall asymmetry.

This is an observational study posing that using the conventional VWS to understand the rainfall asymmetry of TC is inopportune. The conventional VWS can only largely grasp the rainfall asymmetry in the inner core of TC, but not in the outer core. Table 2 shows that the correlations between the directions of conventional VWS and the locations of rainfall maxima in the outer core are indeed weak. The overall correlation coefficient is \( -0.37 \) (\( p < 0.001 \)). Therefore, a new VWS, namely effective VWS, dedicated to comprehending the rainfall asymmetries in both the inner and outer cores of TC is proposed to fill this gap using the state-of-art GPM and ERA5 data. Results suggest that the effective shear layer responsible for the rainfall asymmetry should be a function of TC intensity and core region (see Table 1). The effective
shear layer tops are found to increase with TC intensity and decrease from the inner core to the outer core. Although the effective VWS makes no apparent advancement for interpreting the rainfall asymmetry in the inner core, it does in the outer core considerably. Table 2 shows that the correlations between the directions of the effective shears and the locations of rainfall maxima in the outer core are evidently higher than the conventional ones. The overall correlation coefficient in the outer core is substantially enhanced to 0.65 ($p < .001$). The effective VWS is therefore much more generic than the conventional VWS in determining the rainfall asymmetries. The maximum rainfall is likely found on the down-effective-shear to, particularly, down-effective-shear-left side. In addition, the rainfall asymmetry is observed to increase with VWS in both the inner and outer cores. Nonetheless, the distributions of rainfall maxima are relatively scattered for the TCs at higher intensity because of the higher inertial stability.

The effective VWS is shown to be the main factor leading to the TC rainfall asymmetries in both the inner-core and outer-core regions, whereas the MFC exhibits negligible contribution. The correlations between the directions of MFC and the locations of rainfall maxima are weak (Table 2), suggesting the spatial variation of rainfall asymmetries varies very large with MFC. The rainfall maxima found on the maximum MFC region are likely in response to the effective VWS. In addition, the motion of TC is shown to have little contribution to the rainfall asymmetry.

Figure 11 shows the conceptual diagram of the effective VWS proposed in this study. The effective shear layer tops for the inner-core rainfall asymmetry are typically higher than those for the outer core. It is because the

![Figure 9](image-url)
FIGURE 10  As in Figure 6, but for the distributions of the TC rainfall maxima for different angles of separation between the weak effective shear ($|S| \leq 5 \text{ m s}^{-1}$) and fast TC motion ($|T| > 5 \text{ m s}^{-1}$) vectors (each $\pm 15^\circ$, indicated by semi-transparent purple sectors)
upward motion in the inner core is stronger than that in the outer core on average. The convection in the inner core is therefore deeper, and hence, the deeper effective shear layer for the inner-core rainfall asymmetry should be considered. Similarly, the TC at higher intensity possesses stronger updraft such that the deeper convection, and thus, the higher effective shear layer top is attained.

Inspiringly, the angle difference between the proposed effective shears for the inner-core and outer-core rainfall asymmetries is introduced. It helps understanding the spirality of the TC rainfall asymmetries, that is, the fashions or patterns of the rainbands. It is noteworthy that this is what the conventional shear cannot comply. This observational study, therefore, advances the understanding of this, improves the relevant predictability, and provides scientific support for disaster prevention and mitigation. Nevertheless, the current study only investigates the TCs over the western North Pacific.

### Table 2

Circular correlations of the MFC, conventional and proposed effective VWS directions with the maximum rainfall locations of TCs at different intensity (I) and in different core regions (R)

|                | MFC | Conventional VWS (V_{200}−V_{850}) | Effective VWS (V_{top(I,R)}−V_{base(I,R)}) |
|----------------|-----|------------------------------------|---------------------------------------------|
| **Inner core** |     |                                    |                                             |
| TD             | 0.34** | 0.53**                            | 0.56**                                       |
| TS–STS         | 0.12** | 0.57**                            | 0.60**                                       |
| TY–STY         | 0.00   | 0.61**                            | 0.61**                                       |
| SuperT         | 0.07   | 0.27**                            | 0.27**                                       |
| All            | 0.14** | 0.60**                            | 0.59**                                       |
| **Outer core** |     |                                    |                                             |
| TD             | 0.44** | 0.54**                            | 0.61**                                       |
| TS–STS         | −0.36** | −0.37**                           | 0.67**                                       |
| TY–STY         | −0.01  | −0.21**                           | 0.20**                                       |
| SuperT         | −0.09  | −0.13*                            | 0.33**                                       |
| All            | −0.25** | −0.37**                           | 0.65**                                       |

*Denote the statistical significance at the 95% confidence level.
**Denote the statistical significance at the 99.9% confidence level.

**Figure 11** Conceptual diagram of the effective shears ($S_i$ and $S_o$) responsible for the inner-core and outer-core rainfall asymmetries of TC. Arrows indicate the flows of motion. Clusters depict the convective towers or rainbands. $S_i$ {\text{top}}$ and $S_i$ {\text{base}} denote the effective shear layer top and effective shear layer base responsible for the inner-core rainfall asymmetry, while $S_o$ {\text{top}}$ and $S_o$ {\text{base}} denote the effective shear layer top and effective shear layer base responsible for the outer-core rainfall asymmetry. $V_i$ {\text{top}}$ and $V_i$ {\text{base}} denote the environmental horizontal winds at the $S_i$ {\text{top}}$ and $S_i$ {\text{base}}$, while $V_o$ {\text{top}}$ and $V_o$ {\text{base}} denote the environmental horizontal winds at the $S_o$ {\text{top}}$ and $S_o$ {\text{base}}.
examination of the TCs over the other ocean basins would be informatively indispensable which forms the next step of the study. Future work like model validation and evaluation are also warranted. Moreover, the present work could give valuable insights into the rainfall asymmetries of TCs prior to, during, and after landfall. As land can modify the lower-tropospheric flow due to various topography effects, the effective shear would be altered, and hence, could contribute to the rainfall distribution. Further investigations on this are precious.

Notably, as the proposed effective VWS in this study is generalized from thousands of observations, this work suggests a qualitative framework providing generic understanding of the TC rainfall asymmetry. In reality, the effective VWS leading to rainfall asymmetry is much more complex. The modelling studies on the explicit formulations or matrices of the framework are urged.

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DATA AVAILABILITY STATEMENT
The JTWC best-track data were extracted from https://www.ncdc.noaa.gov/ibtracs/. The IMERG precipitation data were retrieved from https://www.nasa.gov/mission_pages/GPM/main/index.html. The ERA5 reanalysis data were downloaded from https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5.

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REFERENCES
Banacos, P.C. and Schultz, D.M. (2005) Use of moisture flux convergence in forecasting convective initiation: historical and operational perspectives. Weather and Forecasting, 20, 351–366. https://doi.org/10.1175/WAF858.1.
Burpee, R.W. and Black, M.L. (1989) Temporal and spatial variations of rainfall near the centers of two tropical cyclones. Monthly Weather Review, 117, 2204–2218. https://doi.org/10.1175/1520-0493(1989)117<2204:TAVOR>2.0.CO;2.
Cao, X., Chen, S.F., Chen, G.H. and Wu, R.G. (2016) Intensified impact of northern tropical Atlantic SST on tropical cyclogenesis frequency over the western North Pacific after the late 1980s. Advances in Atmospheric Sciences, 33, 919–930. https://doi.org/10.1007/s00376-016-5206-z.
Cecil, D.J. (2007) Satellite-derived rain rates in vertically sheared tropical cyclones. Geophysical Research Letters, 34, L02811. https://doi.org/10.1029/2006GL027942.
Chan, J.C.L., Liu, K.S., Ching, E. and Lai, E.S.T. (2004) Asymmetric distribution of convection associated with tropical cyclones making landfall along the South China coast. Monthly Weather Review, 132, 2410–2420. https://doi.org/10.1175/1520-0493(2004)132<2410:ADOCAW>2.0.CO;2.
Chan, K.T.F., Chan, J.C.L. and Wong, W.K. (2019) Rainfall asymmetries of landfalling tropical cyclones along the South China coast. Meteorological Applications, 26, 213–220. https://doi.org/10.1002/met.1754.
Chen, C., Chen, Q., Duan, Z., Zhang, J., Mo, K. and Li, Z. (2018) Multiscale comparative evaluation of the GPM IMERG v5 and TRMM 3B42 v7 precipitation products from 2015 to 2017 over a climate transition area of China. Remote Sensing, 10, 944–962. https://doi.org/10.3390/rs10060944.
Chen, S.S., Knaff, J.A. and Marks, F.D. (2006) Effects of vertical wind shear and storm motion on tropical cyclone rainfall asymmetries deduced from TRMM. Monthly Weather Review, 134, 3190–3208. https://doi.org/10.1175/MWR2345.1.
Corbosiero, K.L. and Molinari, J. (2002) The effects of vertical wind shear on the distribution of convection in tropical cyclones. Monthly Weather Review, 130, 2110–2123. https://doi.org/10.1175/1520-0493(2002)130<2110:TEOVWS>2.0.CO;2.
Corbosiero, K.L. and Molinari, J. (2003) The relationship between storm motion, vertical wind shear, and convective asymmetries in tropical cyclones. Journal of the Atmospheric Sciences, 60, 366–376. https://doi.org/10.1175/1520-0469(2003)060<0366:TRBSMV>2.0.CO;2.
DeMaria, M. (1996) The effect of vertical wind shear on tropical cyclone intensity change. Journal of the Atmospheric Sciences, 53, 2076–2088. https://doi.org/10.1175/1520-0469(1996)053<2076:TEOVWS>2.0.CO;2.
Frank, W.M. and Ritchie, E.A. (1999) Effects of environmental flow upon tropical cyclone structure. Monthly Weather Review, 127, 2044–2061. https://doi.org/10.1175/1520-0493(1999)127<2044:EOEFUT>2.0.CO;2.
Frank, W.M. and Ritchie, E.A. (2001) Effects of vertical wind shear on the intensity and structure of numerically simulated hurricanes. Monthly Weather Review, 129, 2249–2269. https://doi.org/10.1175/1520-0493(2001)129<2249:EOVWSO>2.0.CO;2.
Gao, Q., Li, Q. and Dai, Y. (2020) Characteristics of the outer rainband stratiform sector in numerically simulated tropical cyclones: lower-layer shear versus upper-layer shear. Advances in Atmospheric Sciences, 37, 399–419. https://doi.org/10.1007/s00376-020-9202-y.
Gao, S., Zhai, S., Li, T. and Chen, Z. (2018) On the asymmetric distribution of shear-relative typhoon rainfall. Meteorology and Atmospheric Physics, 130, 11–22. https://doi.org/10.1007/s00703-016-0499-0.
Gao, Y., Leung, L.R., Salathé, E.P., Dominguez, F., Njissen, B. and Lettenmaier, D.P. (2012) Moisture flux convergence in regional and global climate models: implications for droughts in the southwestern United States under climate change. Geophysical Research Letters, 39, L097119. https://doi.org/10.1029/2012GL051560.
Hou, A.Y., Kakar, R.K., Neeck, S., Azarbarzin, A.A., Kummerow, C. D., Kojima, M., Oki, R., Nakamura, K. and Iguchi, T. (2013) The global precipitation measurement mission. American Ceramic Society Bulletin, 95, 701–722. https://doi.org/10.1175/bams-d-13-00164.1.

Huffman, G.J., Bolvin, D., Braithwaite, T., Hsu, D.K., Joyce, R., Kidd, C., Nelkin, E.J. and Xie, P. (2012) Developing the integrated multi-satellite retrievals for GPM (IMERG). Acta Paulista De Enfermagem, 25, 146–150. https://doi.org/10.1590/S0103-21002012000100025.

Jones, S.C. (1995) The evolution of vortices in vertical shear. I: initially barotropic vortices. Quarterly Journal of the Royal Meteorological Society, 121, 821–851. https://doi.org/10.1002/qj.49712152406.

Kim, D., Ho, C.H., Park, D.S.R., Chan, J.C.L. and Jung, Y. (2018) The relationship between tropical cyclone rainfall area and environmental conditions over the subtropical oceans. Journal of Climate, 31, 4605–4616. https://doi.org/10.1175/jcli-d-17-0712.1.

Kim, D., Ho, C.H., Park, D.S.R., Kim, J. and Nie, J. (2019) Influence of vertical wind shear on wind- and rainfall areas of tropical cyclones making landfall over South Korea. PLoS One, 14, e0209885. https://doi.org/10.1371/journal.pone.0209885.

Li, T. (2005) Origin of the summertime synoptic-scale wave train in the western North Pacific. Journal of the Atmospheric Sciences, 63, 1093–1102. https://doi.org/10.1175/jas3676.1.

Lin, Z., Lu, R. and Zhou, W. (2010) Change in early-summer meridional teleconnection over the western North Pacific and East Asia around the late 1970s. International Journal of Climatology, 30, 2195–2204. https://doi.org/10.1002/joc.2038.

Liu, K.S., Chan, J.C.L., Cheng, W.C., Tai, S.L. and Wong, P.W. (2007) Distribution of convection associated with tropical cyclones making landfall along the South China coast. Meteorology and Atmospheric Physics, 97, 57–68. https://doi.org/10.1007/s00703-006-0244-1.

Lonfat, M., Marks, F.D. and Chen, S.S. (2004) Precipitation distribution in tropical cyclones using the tropical rainfall measuring Mission (TRMM) microwave imager: a global perspective. Monthly Weather Review, 132, 1645–1660. https://doi.org/10.1175/1520-0493(2004)132<1645:PDTCM>2.0.CO;2.

Marks, F.D. (1985) Evolution of the structure of precipitation in Hurricane Allen (1980). Monthly Weather Review, 113, 909–930. https://doi.org/10.1175/1520-0493(1985)113<0909:ESOP>2.0.CO;2.

Pei, Y. and Jiang, H. (2018) Quantification of precipitation asymmetries of tropical cyclones using 16-year TRMM observations. Journal of Geophysical Research- Atmospheres, 123, 8091–8114. https://doi.org/10.1029/2018JD028545.

Rao, V.B., Ferreira, C.C., Franchito, S.H. and Ramakrishna, S.S.V.S. (2008) In a changing climate weakening tropical easterly jet induces more violent tropical storms over the North Indian Ocean. Geophysical Research Letters, 35, L15710. https://doi.org/10.1029/2008gl034729.

Rodgers, E.B., Baik, J.J. and Pierce, H.F. (1994) The environmental influence on tropical cyclone precipitation. Journal of Applied Meteorology and Climatology, 33, 573–593. https://doi.org/10.1175/1520-0450(1994)033<0573:TEIOTC>2.0.CO;2.

Rogers, R., Chen, S., Tenerelli, J. and Willoughby, H. (2003) A numerical study of the impact of vertical shear on the distribution of rainfall in hurricane Bonnie (1998). Monthly Weather Review, 131, 1577–1599. https://doi.org/10.1175/2546.1.

Ueno, M. (2007) Observational analysis and numerical evaluation of the effects of vertical wind shear on the rainfall asymmetry in the typhoon inner-core region. Journal of the Meteorological Society of Japan, 85, 115–136. https://doi.org/10.2151/jmsj.85.115.

Wang, Y. and Holland, G.J. (1996) Tropical cyclone motion and evolution in vertical shear. Journal of the Atmospheric Sciences, 53, 3313–3332. https://doi.org/10.1175/1520-0469(1996)053<3313:TCMCIE>2.0.CO;2.

Wen, G., Huang, G., Huang, H., Liu, C. and Bi, X. (2019) Observed rainfall asymmetry of tropical cyclone in the process of making landfall in Guangdong, South China. International Journal of Climatology, 39, 3379–3395. https://doi.org/10.1002/joc.6027.

Wingo, M.T. and Cecil, D.J. (2010) Effects of vertical wind shear on tropical cyclone precipitation. Monthly Weather Review, 138, 645–662. https://doi.org/10.1175/2009MWR2921.1.

Xu, W., Jiang, H. and Kang, X. (2014) Rainfall asymmetries of tropical cyclones prior to, during, and after making landfall in South China and Southeast United States. Atmospheric Research, 193, 18–26. https://doi.org/10.1016/j.atmosres.2013.12.015.

Yu, Z., Wang, Y. and Xu, H. (2015) Observed rainfall asymmetry in tropical cyclones making landfall over China. Journal of Applied Meteorology and Climatology, 54, 117–136. https://doi.org/10.1175/JAMC-D-13-0359.1.

Zheng, X., Duan, Y. and Yu, H. (2007) Dynamical effects of environmental vertical wind shear on tropical cyclone motion, structure, and intensity. Meteorology and Atmospheric Physics, 97, 207–220. https://doi.org/10.1007/s00703-006-0253-0.

Zomereren, J.V. and Delden, A.V. (2007) Vertically integrated moisture flux convergence as a predictor of thunderstorms. Atmospheric Research, 83, 435–445. https://doi.org/10.1016/j.atmosres.2005.08.015.

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