




RESEARCH ARTICLE

Rainfall asymmetries of landfalling tropical cyclones along the South China coast

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Funding information

Hong Kong Research Grants Council of the Hong Kong Special Administrative Region of China, Grant/Award Number: 11301417; City University of Hong Kong, Grant/Award Number: 7004469

The rainfall distribution associated with landfalling tropical cyclones (TCs) along the South China coast are examined using radar data from Hong Kong Observatory (HKO). This preliminary study relates the landfall direction, and possible rotations/transitions of TC rainfall asymmetries before and after the landfall. Three types of landfalling TCs on the South China coast are categorized: from the east, normal to the coast and from the southwest. For those from the east, the rainfall maximum rotates anticyclonically from the southwest before later landfall to the northwest. TCs making landfall perpendicular to the coast have a rainfall maximum remaining in the southwest quadrant throughout the landfall process. For TCs making landfall from the southwest, the rainfall maximum rotates cyclonically from the southeast before later landfall to the northeast. The relative importance of the impact of land properties and vertical wind shear on these rainfall asymmetries is investigated by using a numerical model. Sensitivity tests show that the rotations/transitions of landfalling TC rainfall asymmetry appear to be insensitive to land properties (e.g. moisture availability, surface friction and topography), but result primarily from changes in the orientations of the vertical wind shear in the environment. However, the surface friction of the landmass appears to contribute to the enhancement of rainfall intensity.

KEYWORDS

asymmetry, landfall, land property, rainfall, tropical cyclone

1 | INTRODUCTION

The impacts of a tropical cyclone (TC) as it makes landfall include storm surges, heavy rainfall and strong winds. Such impacts on a particular place depend on its location relative to where the TC makes landfall. Along coastal areas, a storm surge is often the greatest threat to life and property (e.g. Irish *et al.*, 2008; Seo and Bakkensen, 2017), followed by flooding and landslips caused by the heavy rain (e.g. Marks and Shay, 1998; Rappaport, 2000; Chien and Kuo, 2011). The ability to predict specific regions that will experience heavy rain is therefore very important in disaster mitigation.

Other than the strong symmetric circulation near the centre, the TC structure is generally asymmetric. The relatively weaker asymmetric features, such as environmental vertical wind shear (VWS) (e.g. Jones, 1995; DeMaria, 1996; Frank

and Ritchie, 1999), TC motion (e.g. Shapiro, 1983; Lonfat *et al.*, 2004), the interaction with synoptic systems (e.g. Bender, 1997; Persing *et al.*, 2002; Yu *et al.*, 2015) and non-uniform surface characteristics (e.g. Bosart *et al.*, 2000; Chen and Yau, 2003) could all lead to asymmetries. Previous studies have shown that TCs over oceans and those making landfall have significant rainfall or convective activity asymmetries (e.g. Corbosiero and Molinari, 2002; Chan *et al.*, 2004; Chen *et al.*, 2006; Cecil, 2007; Liu *et al.*, 2007; Ueno, 2007). The studies identified a preference for upward motion, rainfall and lightning in the downshear or downshear-left side of the TCs in the Northern Hemisphere.

Although many studies have investigated the TC rainfall asymmetries based on both the observations and numerical models, those focusing on TCs making landfall along the South China coast are limited (e.g. Chan *et al.*, 2004; Liu *et al.*, 2007; Xu *et al.*, 2014; Yu *et al.*, 2015). In addition,

the impacts of land properties on landfalling TC rainfall asymmetries on the South China coast have received little attention and have not been systematically documented (e.g. Li *et al.*, 2013; Li *et al.*, 2014, 2015). These form the foci of the present study.

Rather than a single-case, composite or pure modelling study, the present paper will first examine 13 individual TC landfall cases to identify the rainfall asymmetries before and after TC landfall based on the landfall direction of the TC. To investigate the impacts and relative importance of land properties and VWS on these asymmetries, a series of numerical sensitivity experiments are carried out, and the results are presented. A summary of the study together with future directions is then given.

2 | CATEGORIZATION OF LANDFALLING TROPICAL CYCLONE RAINFALL ASYMMETRIES

In this study, the TC best tracks and 3 km constant altitude plan position indicator (CAPPI) radar data from Hong Kong Observatory (HKO) are used as the best estimates of TC positions and the proxy of TC rainfall respectively. The radar data were retrieved by Doppler radars located at Tai Mo Shan (22.4° N, 114.1° E) and Tate's Cairn (22.4° N, 114.2° E), Hong Kong. The maximum reflectivity among the two radars was extracted when both radars were available. The temporal, horizontal resolution and radial coverage of the radar data were 6 min, 1.07 and 256 km respectively. HKO began archiving the data from the current radars in 1999. Therefore, all TCs that could be largely scanned by the two HKO radars and which made landfall along the South China coast between 1999 and 2016 were investigated (13 cases in total; Table 1). The transition period from 6 hr before to 6 hr after landfall was mainly analysed in this study.

By categorizing the incidence angle (i.e. the landfall direction), these 13 landfalling TCs could be categorized into three types (Figure 1 and Table 1). The convection distribution of all TCs within each type was found to be very similar. Therefore, only one case in each type will be discussed in greater detail:

- Type A has two TCs, Maggie and Dujuan, that made landfall on the South China coast from the east (Figure 2a for Dujuan). The rainfall maximum associated with both TCs rotates anticyclonically from the southwest quadrant of the TC before later landfall to the northwest (Figure 2b,c for Dujuan; similar for Maggie, data not shown).
- Type B is the most common, with a total of 10 TCs (Sam, York, Maria, Kompas, Fengshen, Nuri, Molave, Vicente, Nida and Haima). All made landfall on the South China coast from the southeast (see the example in

TABLE 1 Landfalling tropical cyclones on the South China coast in 1999–2016 and their categorizations in this study

Type	Year	Name
A	1999	Maggie
A	2003	Dujuan
B	1999	Sam
B	1999	York
B	2000	Maria
B	2004	Kompasu
B	2008	Fengshen
B	2008	Nuri
B	2008	Molave
B	2012	Vicente
B	2016	Nida
B	2016	Haima
C	2002	Kammuri

Figure 2d for Nuri). In this type, the rainfall maximum remains in the same southwest quadrant of the TC before, during and after landfall (Figure 2e,f for Nuri; the other nine TCs have similar patterns, data not shown).

- Type C has only one case, Kammuri, a TC that made landfall on the South China coast from the southwest (Figure 2g). Its rainfall maximum rotated cyclonically from the southeast quadrant of the TC before later landfall to the northeast (Figure 2h,i).

It appears that from this limited sample that the most common situation is landfall from the southeast (Type B), with the rainfall being maximum to the southwest, which is consistent with the previous observational results of Chan *et al.* (2004). The other two types are less common and only a few cases can be found within the period during which HKO radar data are available. The observed rotation of the rainfall maximum should therefore be treated with caution, and clearly more cases need to be examined. Nevertheless, it would still be useful to investigate how the possible factors such as VWS (e.g. Corbosiero and Molinari, 2002; Chen *et al.*, 2006; Cecil, 2007; Ueno, 2007) and land properties (e.g. Li *et al.*, 2013, 2014, 2015), such as moisture availability, surface friction and topography, may contribute to the different distributions of convection for TCs making landfall from different directions. The results of such an investigation are presented in the next section.

3 | SIMULATION RESULTS

To examine the impacts of land properties on the rainfall asymmetry of the landfalling TC, a series of numerical modelling experiments were conducted for each type of landfalling TC using the Weather Research and Forecasting Model (WRF) Version 3.9. The model domain was triply nested with two-way interactive nesting and the inner

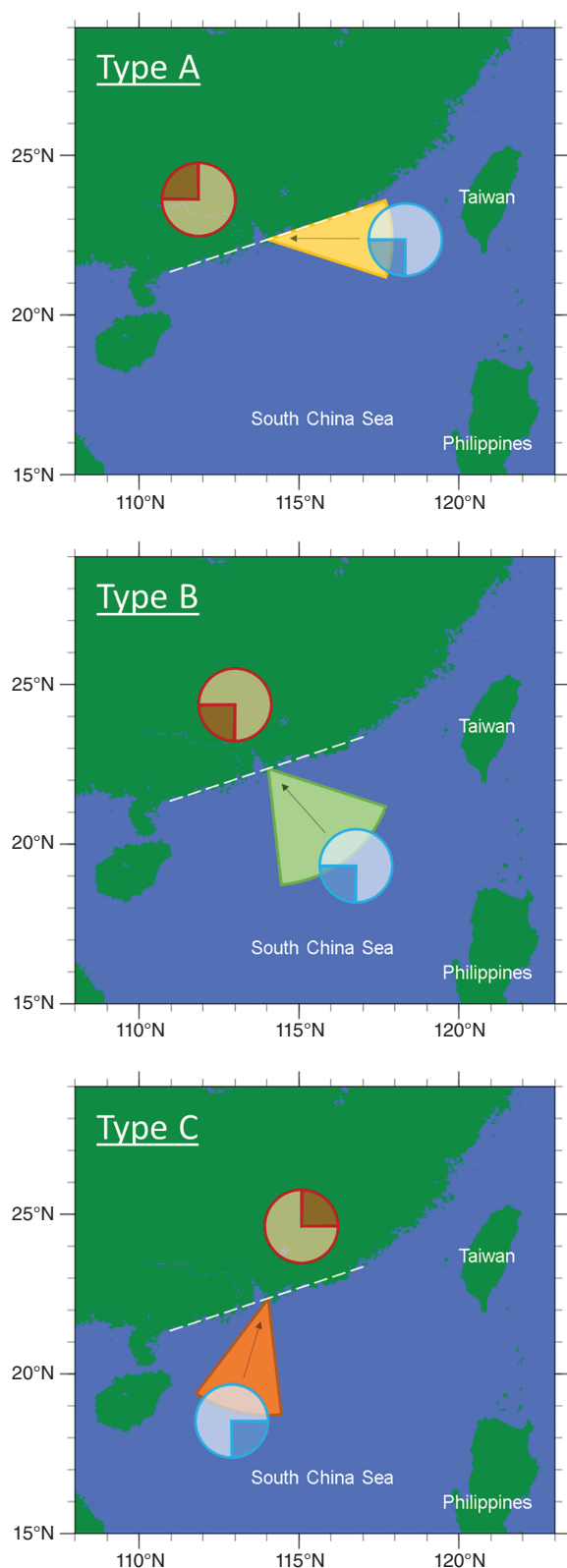


FIGURE 1 Categorization of landfalling tropical cyclones (TCs) on the South China coast based on the landfall directions and rotations/transitions of TC rainfall asymmetries before and after the landfall. Dashed lines denote the approximation of the coast used in this study. Large pie shapes with arrows denote the ranges of the angle of attack on the coast in corresponding types. Discs with dark quarters indicate the TC rainfall asymmetries before and after landfall respectively

meshes are automatically vortex following. The horizontal resolutions of the meshes are 36, 12 and 4 km; the corresponding domain sizes are $4,356 \times 3,600$, $2,388 \times 2,388$ and $1,000 \times 1,000$ km² respectively. The outermost static domain is centred on Hong Kong (22.4° N, 114.0° E). The model has 36 terrain-following σ levels with higher vertical resolution in the planetary boundary layer and the reference model top pressure is 50 hPa. For the model physics, the five-layer thermal diffusion, MM5 similarity surface layer physics (Jiménez *et al.*, 2012) and Yonsei University planetary boundary layer scheme (Hong *et al.*, 2006) were used. The WRF Single-Moment six-class scheme (Hong and Lim, 2006) and Rapid Radiative Transfer Model for the general circulation models (RRTMG) radiation scheme (Iacono *et al.*, 2008) were taken to model the microphysics, and short wave and long wave radiation physics respectively. The Tiedtke cumulus parameterization scheme (Tiedtke, 1989; Zhang *et al.*, 2011) was used in the outer two domains only. The initial and boundary conditions were initialized and six-hourly updated by the National Centers for Environmental Protection (NCEP) Climate Forecast System Reanalysis (CFSR) data (Skamarock *et al.*, 2008).

In each type of landfalling TCs, six experiments were designed to test the sensitivity and relative importance of moisture availability, surface friction and topography of the landmass on the rainfall of landfalling TCs on the South China coast (Table 2): (1) control, (2) dry landmass, (3) wet landmass, (4) water terrain, (5) flat coast and (6) flat coast and water terrain. In the control experiment, the default land-use properties from the WRF were employed. In the dry landmass and wet landmass experiments, the moisture availabilities over land were set to 0% and 100% respectively to test the importance of moisture. In the water terrain experiment, the land use of all terrain was set to those of water to test the importance of friction over land. In the flat coast experiment, the terrain height of South China was set to zero to investigate the effect of topography. Lastly, the flat coast and water terrain experiment was the combination of both the flat coast and water terrain specifications.

For each type, the sensitivity experiments were run for the case selected above, that is, TCs Dujuan (Type A), Nuri (Type B) and Kammuri (Type C). The simulated TC tracks in the control experiments matched well with the best tracks in view of landfall locations and directions in general (Figure 2a,d,g). The simulated tracks for all the other experiments were also similar, which suggests the land properties appear to have very little impact on the tracks of landfalling TCs.

Only the control and water terrain experiments are shown because the latter shows obvious differences. For further discussion, see the text. The other experiments give results quite similar to those in the control experiment and therefore are not shown. In TC Dujuan (Type A), all six numerical experiments captured the rotation of the rainfall asymmetry (e.g. Figure 3a,b) as that observed by the radar

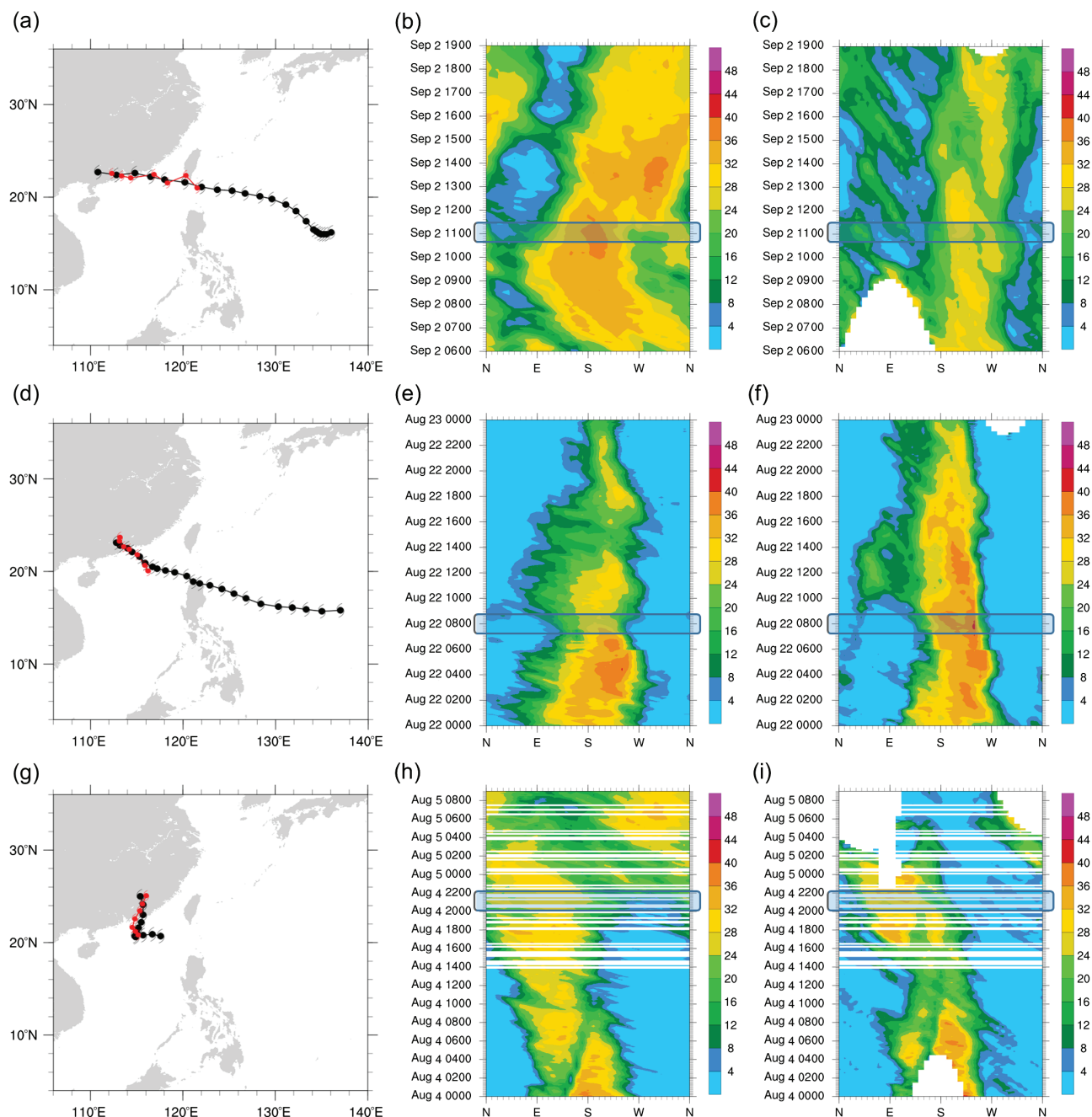


FIGURE 2 Six-hourly best tracks (black) and simulated tracks (red) of the control experiments (left column); and Hovmöller diagrams of the averages of 3 km constant altitude plan position indicator (CAPPI) reflectivity (dBZ) at each 10° azimuth within a radius of 0–100 km (middle column) and 100–200 km (right column) from the tropical cyclone (TC) centre. TCs: (a–c) Dujuan, (d–f) Nuri and (g–i) Kammuri. The half-transparent strips specified in the Hovmöller diagrams denote the time near landfall of each corresponding storm. Regions shown in white represent missing data due to radar unavailability and/or encountering the landmass

TABLE 2 Experimental designs of six sensitivity experiments

Experiment	Moisture availability	Land use	Terrain height
Control	Default	Default	Default
Dry landmass	0%	Default	Default
Wet landmass	100%	Default	Default
Water terrain	Default	Water	Default
Flat coast	Default	Default	0 m on the South China coast
Flat coast and water terrain	Default	Water	0 m on the South China coast

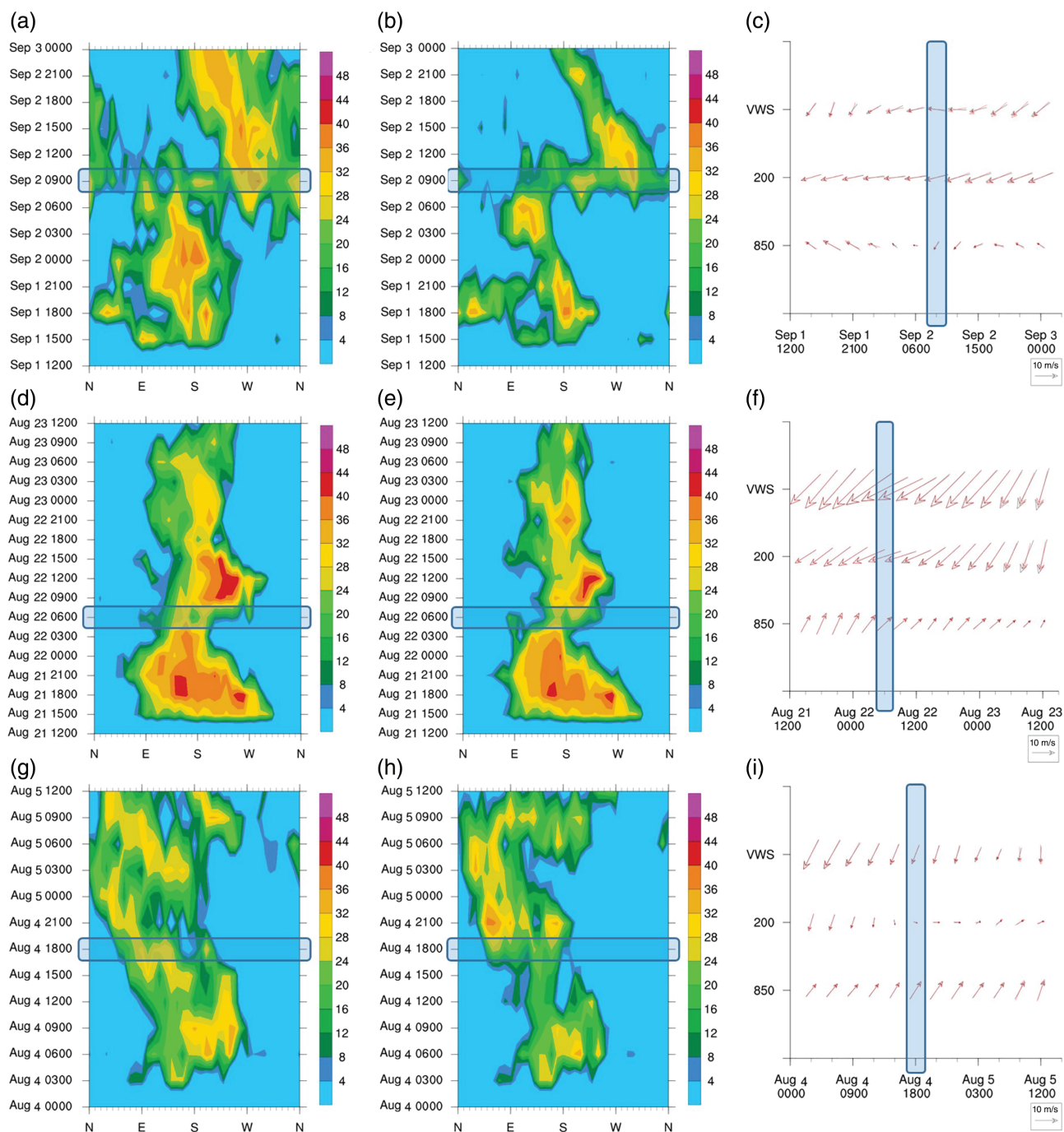


FIGURE 3 Hovmöller diagrams of the averages of 3 km modelled reflectivity (dBZ) at each 10° azimuth within a radius of 0–200 km from the tropical cyclone (TC) centre. TCs: (a–c) Dujuan, (d–f) Nuri and (g–i) Kammuri in the control (left column) and water terrain (middle column) experiments. Figures in the right column are the time-series of the vertical wind shear (VWS) and averaged horizontal winds at 200 and 850 hPa pressure levels within 600 km from the centre of a particular TC. Vectors in black and red indicate the model results from the control and water terrain experiments respectively. The half-transparent strips denote the approximate time of landfall for each corresponding storm

(Figure 2b,c). The rainfall maximum rotates anticyclonically from the southeast before later landfalling to the northwest. Similarly, experiments for TCs Nuri (Type B) and Kammuri (Type C) reproduce the corresponding transitions of landfalling TC rainfall asymmetries. The rainfall maximum remains to the southwest in TC Nuri (e.g. Figure 3d,e), whereas it rotates cyclonically from the southeast before and then to the northeast after landfall in TC Kammuri (e.g. Figure 3g,h).

Note, however, that no obvious difference in the rotation/transition of landfalling TC rainfall asymmetry was found among the various experiments. This implies the rotation/transition of rainfall asymmetry of landfalling TC is not sensitive to the land properties. Instead, it was found to be mainly determined by the orientation of the VWS from the environment (e.g. Figure 3c,f), such that the rainfall maximum is generally found at the downshear or downshear-left

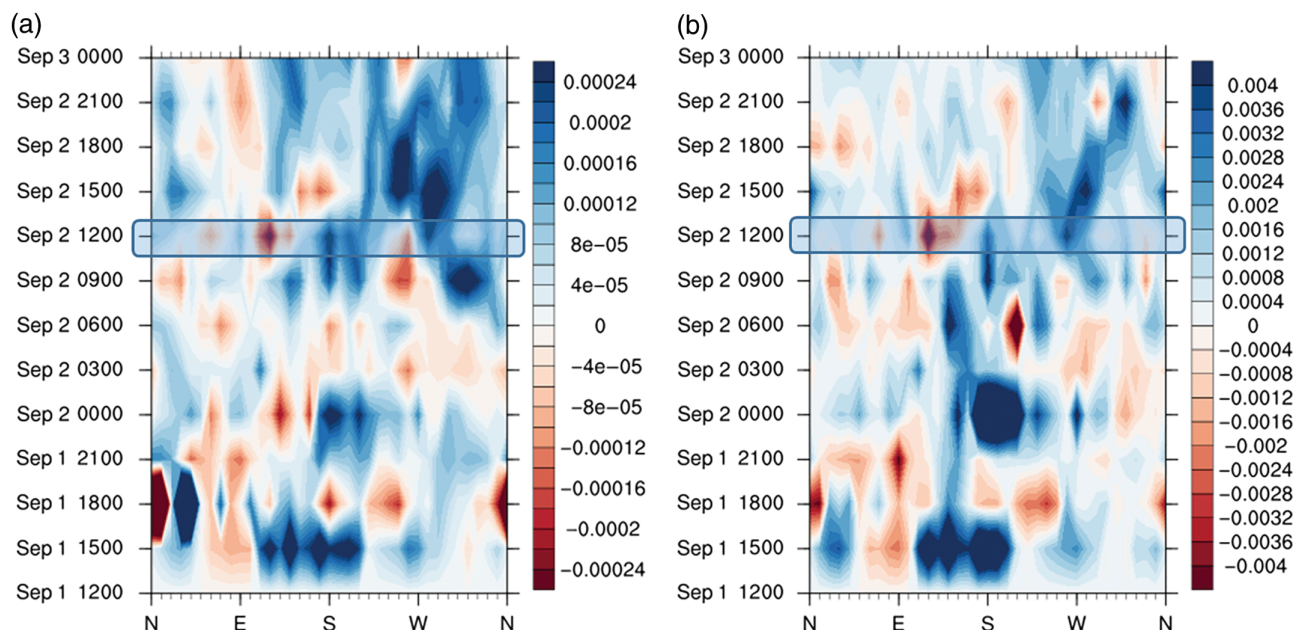


FIGURE 4 Hovmöller diagrams of the differences between the control and water terrain experiments (i.e. control – water terrain) of the averages for (a) lower tropospheric wind convergence at $\sigma = 0.944$ km/s; and (b) moisture flux convergence ($\text{kg m}^{-2} \text{s}^{-1}$) at each 10° azimuth within a radius of 0–200 km from the centres of tropical cyclone Dujuan. Positives and negatives mean more and less convergence in the control experiment respectively. The half-transparent strips denote the approximate time of landfall

side, which is consistent with the results of previous studies (e.g. Corbosiero and Molinari, 2002; Chen *et al.*, 2006; Cecil, 2007; Ueno, 2007). In this study, the VWS is calculated as the difference in averaged horizontal winds between 200 and 850 hPa over an area with a radius of 600 km from the TC centre. The modelled VWS matches well with the reanalysis data, the Modern-Era Retrospective Analysis for Research and Applications Version 2 (MERRA-2) from the National Aeronautics and Space Administration (NASA) (data not shown).

Combining the above results, it could be concluded that different types of TC landfall on the South China coast may likely experience different VWS orientations, and hence the different convection asymmetries. Such orientations might be related to the landfall direction as the latter is largely related to the vertically integrated steering flow, and hence the VWS. Further investigation would be necessary to ascertain this relationship. Internal dynamics might also slightly contribute to the VWS (Li *et al.*, 2015).

Numerical results show that the land properties do not modify the background wind around the vortex much, even in the lower troposphere, and hence the VWS is not changed (e.g. Figure 3c,f,i). This could be one reason why no apparent difference in the rotation/transition of landfalling TC rainfall asymmetry is found in the experiments. However, Li *et al.* (2014) and Yu *et al.* (2017) found that the asymmetric rainfall maximum is more likely to be located on the off- and onshore sides respectively, which are different from the conclusion drawn in the present study. Such discrepancies may be understood from the approaches taken by these authors: Li *et al.* performed idealized numerical experiments in the Southern Hemisphere without any environmental VWS,

while Yu *et al.* performed a composite study of satellite-derived rainfall for TC landfall along the entire China coast.

Although the sensitivity experiments did not show that land properties have any significant impact on rainfall distribution, the results of the experiments with water terrain in all three types are distinct from those in the other experiments. In the former, the rainfall intensity is less than that in the corresponding control experiment (e.g. cf. Figure 3a,b,d, e,g,h). The results of the other sensitivity experiments are similar to those of the control and therefore are not shown. This implies the surface friction is likely an important factor in affecting the rainfall intensity of a landfalling TC. The water budget diagnostic shows that the moisture flux convergence matches well with the lower tropospheric wind convergence (data not shown). This suggests the landmass has higher surface friction (e.g. the control experiment) and induces higher wind convergence at the lower troposphere (Figure 4a), which enhances the convection and moisture flux convergence (Figure 4b), and thus results in higher rainfall intensity (e.g. Figure 3a,b).

4 | CONCLUSIONS AND SUMMARY

Many studies have investigated tropical cyclone (TC) rainfall asymmetries based on both observations and numerical models. However, those focusing on TCs making landfall along the South China coast are limited (e.g. Chan *et al.*, 2004; Xu *et al.*, 2014; Yu *et al.*, 2015). In addition, the impacts of land properties on landfalling TC rainfall asymmetry on the South China coast have received little

attention and are not specially documented. These form the foci of this study.

Based on 13 landfalling TCs in proximity to Hong Kong during the period 1999–2016, three types of landfalling TC rainfall asymmetries on the South China coast were proposed using radar data. In Type A, a TC makes landfall on the South China coast from the east and the corresponding rainfall maximum rotates anticyclonically from the southwest quadrant of the TC before landfall, and then later to the northwest. In Type B, the most common type, the TC makes landfall on the coast from the southeast and the corresponding rainfall maximum remains in the same southwest quadrant of the TC throughout the whole landfall process. In Type C, the TC makes landfall on the coast from the southwest and its associated asymmetric rainfall maximum rotates cyclonically from the southeast quadrant of the TC before landfall, and then later to the northeast.

Numerical modelling experiments show that the rotation/transition of rainfall asymmetry of a landfalling TC on the South China coast is not sensitive to the land properties. Instead, both modelling results and observational analyses show that the rotation/transition of rainfall asymmetry identified with different landfall directions is mainly determined by the orientation of vertical wind shear (VWS) in the environment, although some studies suggest that internal dynamics could also modify the VWS (e.g. Li *et al.*, 2015). As the changes in rainfall asymmetries vary with landfall direction, this suggests that the VWS may likely vary with the steering flow, and hence the subsequent rainfall asymmetries. Further investigations on this point will be necessary. Although the land properties do not modify the rainfall distribution, it could affect rainfall intensity. A landmass with a higher surface friction appears to induce higher wind convergence at the lower troposphere, which enhances the convection and moisture flux convergence, and ultimately results in higher rainfall intensity.

Because of data availability, the sample size of this study is rather limited so that the robustness of the categorization should be treated with caution, especially for those in Types A and C. The next step in this investigation is to assemble a larger data set by incorporating radar and perhaps rain-gauge data from other stations along the China coast to ascertain the results found in this preliminary study. Nevertheless, even with a limited sample size, it might be concluded that rainfall asymmetries do vary with landfall direction. Such a result could be useful in operational forecasting of possible flooding over land.

ACKNOWLEDGEMENTS

The Climate Forecast System Reanalysis (CFSR) data from the National Centers for Environmental Protection (NCEP), as well as MERRA-2 data from the National Aeronautics and Space Administration (NASA) are greatly appreciated.

Data analyses and visualizations were mostly performed by the National Center for Atmospheric Research Command Language Version 6.4.0 (see <https://doi.org/10.5065/D6WD3XH5>). This study was supported by the City University of Hong Kong (grant number 7004469) and by the Hong Kong Research Grants Council of the Hong Kong Special Administrative Region of China (grant number CityU 11301417).

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How to cite this article: Chan KTF, Chan JCL, Wong WK. Rainfall asymmetries of landfalling tropical cyclones along the South China coast. *Meteorol Appl.* 2019;26:213–220. <https://doi.org/10.1002/met.1754>