The Relationship between Tropical Cyclone Rainfall Area and Environmental Conditions over the Subtropical Oceans

DASOL KIM AND CHANG-HOI HO

School of Earth and Environmental Sciences, Seoul National University, Seoul, South Korea

DOO-SUN R. PARK

Department of Earth Sciences, Chosun University, Gwangju, South Korea

JOHNNY C. L. CHAN

Guy Carpenter Asia-Pacific Climate Impact Centre, School of Energy and Environment, City University of Hong Kong, Hong Kong, China

YOUNGSUN JUNG

Center for Analysis and Prediction of Storms, University of Oklahoma, Norman, Oklahoma

(Manuscript received 20 October 2017, in final form 2 March 2018)

ABSTRACT

In this study, the variation of tropical cyclone (TC) rainfall area over the subtropical oceans is investigated using the Tropical Rainfall Measuring Mission precipitation data collected from 1998 to 2014, with a focus on its relationship with environmental conditions. In the subtropics, higher moving speed and larger vertical wind shear significantly contribute to an increase in TC rainfall area by making horizontal rainfall distribution more asymmetric, while sea surface temperature rarely affects the fluctuation of TC rainfall area. This relationship between TC rainfall area and environmental conditions in the subtropics is almost opposite to that in the tropics. It is suggested that, in the subtropics, unlike the tropics, dynamic environmental conditions are likely more crucial to varying TC rainfall area than thermodynamic environmental ones.

1. Introduction

The severity of the damage caused by heavy rainfall of tropical cyclones (TCs) has been highlighted in a number of previous studies (Changnon 2008; Czajkowski et al. 2011, 2017; Rappaport 2014; Park et al. 2015, 2016). An accurate forecast of TC rainfall will contribute to the mitigation of casualties by warning people to stay out of flood-prone areas. Meanwhile, TC rainfall has received less attention than TC wind. It is noted that intensity and size, which are representative characteristics of TCs, are conventionally defined based on TC wind fields such as maximum wind speed and the radius of specific wind speed (Chan and Chan 2012; Knaff et al. 2014; Chavas et al. 2016). A number of operational forecast systems have therefore been developed for TC wind intensity and size—for example, the multimodel and ensemble

prediction system in the Regional Specialized Meteorological Center (RSMC) and Tropical Cyclone Warning Centers (TCWCs; Krishnamurti et al. 2010, 2011; Yu et al. 2013) and the Automated Tropical Cyclone Forecasting System (ATCF; Sampson and Schrader 2000) in the Joint Typhoon Warning Center (JTWC)—but not for TC rainfall.

Numerous studies showed that the spatial distribution of TC rainfall (e.g., radial profiles, spiral rainbands, and asymmetry) is influenced significantly by various environmental conditions such as humidity (Jiang et al. 2008; Hill and Lackmann 2009; Matyas 2010), TC motion induced by steering flow (Frank and Ritchie 1999; Chen et al. 2006), vertical wind shear (Frank and Ritchie 2001; Corbosiero and Molinari 2002; Cecil 2007), planetary vorticity (Bender 1997; Peng et al. 1999), and topography (Chen and Yau 2003; Kimball 2008; Xu et al. 2014). There are a few studies examining the quantitative extent of TC rainfall area and the factors controlling it

Corresponding author: Chang-Hoi Ho, hoch@cpl.snu.ac.kr

DOI: 10.1175/JCLI-D-17-0712.1

© 2018 American Meteorological Society. For information regarding reuse of this content and general copyright information, consult the [AMS Copyright Policy](https://www.ametsoc.org/PUBSReuseLicenses) (www.ametsoc.org/PUBSReuseLicenses).

(Matyas 2010, 2013, 2014; Lin et al. 2015). In the tropics, it was suggested that sea surface temperature (SST) which strongly regulates midtropospheric humidity, controls TC rainfall area as well as TC wind size (Lin et al. 2015; Chavas et al. 2016). These observation-based studies are consistent with the idea that TCs, which can be characterized as heat engines, are basically driven by their thermal environments (Emanuel 1986, 1995b,a). Otherwise, little is known about the general characteristics of the TC rainfall area outside the tropics on a global scale. A TC generally undergoes dramatic changes (e.g., cyclolysis, extratropical transition, and rapid intensification) when it gets out of the tropics because of environmental conditions such as cool SST and strong baroclinity (Bosart et al. 2000; Hanley et al. 2001; Jones et al. 2003). Hence, the relationship between TC rainfall area and environments outside the tropics may be different from that in the tropics. Indeed, several studies investigating specific subtropical regions (e.g., Florida in the United States) have reported that vertical wind shear and diurnal cycles contribute to variations in TC rainfall area (Matyas 2010, 2013, 2014).

This study investigates the relationship between TC rainfall area and environmental conditions over the subtropical band of global oceans. Here, we particularly focus on the influence of SST, TC motion, and vertical wind shear on TC rainfall area for the following reasons. First, TC rainfall area can be affected by SST, which supplies energy to the TC (e.g., Lin et al. 2015). Second, there is a robust relationship between rainfall area and the structural asymmetry of TCs (Lonfat et al. 2007). A large asymmetry is observed when TC movement speed and environmental vertical wind shear are large (Corbosiero and Molinari 2002, 2003; Chen et al. 2006). When a TC moves, asymmetric friction in the boundary layer is induced because of environmental steering flow (Frank and Ritchie 1999; Peng et al. 1999), which causes convergence and divergence at the front-right side and rear-left side of the moving direction, respectively (Shapiro 1983; Bender 1997). Vertical wind shear induces a compensating vertical circulation and potential temperature anomalies in a TC (Jones 1995; DeMaria 1996). Upward and downward motions appear in the downshear-left and upshear-right side, respectively, enhancing asymmetry (Frank and Ritchie 1999, 2001). Meanwhile, the relationship between rainfall area and asymmetry can be shown by a simple example as follows. Asymmetric rainfall field can be expressed as $r = r_0 [1 + \alpha \sin(\theta)]$, where r is distance between the edge of the rainfall field and the TC center, r_0 is the azimuthal mean of r , α is magnitude of the wavenumber-1 asymmetry, and θ is the azimuth angle from the TC center. Thus, the rainfall area is $\pi r_0^2 (1 + 0.5\alpha^2)$ and increases with

asymmetry. Last, it is difficult to examine the effect of other environmental conditions such as planetary vorticity and topography based on observational data. Since the planetary vorticity is a function of latitude, atmospheric and oceanic environments change with planetary vorticity (i.e., latitude). The effect of topography is also very complicated because of various types of topography and complex interaction with other environmental conditions. Therefore, the causal relationship between TC rainfall area and these environmental conditions is hard to estimate explicitly by using observational data. The rest of this paper is organized as follows. Section 2 describes the data and method to estimate TC rainfall area. The variation of TC rainfall area according to environmental conditions is presented in section 3. Finally, the summary of this study is suggested in section 4.

2. Data and methodology

a. Data

TC information, such as track, grade, and maximum wind speed, is obtained from the International Best Track Archive for Climate Stewardship (IBTrACS), which is a global collection of TC best-track datasets (Knapp et al. 2010). Based on the IBTrACS data, only the periods when TCs are classified as tropical storms, which have a maximum wind speed higher than 35 kt ($1 \text{ kt} = 0.51 \text{ m s}^{-1}$), are investigated. TC moving speed is calculated from 6-hourly TC center locations using a central differencing scheme. The SST underlying the TC center is examined using the daily interpolated Optimum Interpolation SST, version 2 (OISSTv2), which covers global oceans with a horizontal resolution of 1° in latitude and longitude (Reynolds et al. 2002). The Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2), reanalysis data (Bosilovich et al. 2015) are used to investigate the atmospheric environmental conditions averaged in the annular region of 200–800 km from the TC center (DeMaria and Kaplan 1994; DeMaria et al. 2005). The vertical wind shear is calculated as the difference between winds at the 250- and 850-hPa pressure levels. The MERRA-2 reanalysis data are provided with a temporal resolution of 1 h, and a horizontal resolution of $0.5^\circ \times 0.625^\circ$ in latitude and longitude, respectively. TC rainfall areas are obtained from the Tropical Rainfall Measuring Mission (TRMM) 3B42 precipitation data (Huffman et al. 2007), which is advantageous for global analysis on TC rainfall because of their high temporal resolution (3-h interval) and wide spatial coverage (global band from 50°S to 50°N) (Jiang and Zipser 2010; Jiang et al. 2011; Lin et al. 2015).

FIG. 1. Global TC tracks during 1998–2014 and locations of six ocean basins. The black lines indicate TC tracks of the subtropics (25° – 35° N and 25° – 35° S) analyzed in this study.

The analysis period spans from the years 1998 to 2014, including periods for which the TRMM-3B42 data are available. Considering the spatial coverage of the TRMM-3B42 data and the maximum potential range of TC rainfall area (i.e., 15° great circle arc from TC center), this study focuses on TCs centered over the global subtropical band (25° – 35° N and 25° – 35° S) in the western North Pacific (WNP), North Atlantic (NA), south Indian (SI), and South Pacific (SP) (Fig. 1). It is notable that considerable TCs appear at higher latitude than the subtropics, but they cannot be examined because of the limitation of observation coverage. The total sample numbers of the subtropical TC rainfall area in the WNP, NA, SI, and SP are 1468, 1123, 515, and 320, respectively. TCs in the eastern North Pacific and the north Indian are excluded because of insufficient sample numbers (i.e., less than 87). The landfall period when the TC center is located over land area is also excluded from the analysis. Additionally, TC rainfall areas in the tropics of global oceans (25° S– 25° N; the total sample number of 10605) are analyzed to compare characteristics of TC rainfall area in the subtropics and the tropics.

b. Methodology to measure TC rainfall area

The algorithm applied to estimate TC rainfall area is based on the methods used in previous studies (Jiang et al. 2011; Matyas 2013, 2014; Lin et al. 2015) with a small modification (Fig. 2). At the beginning of the algorithm, every rain cell within the maximum potential range of TC rainfall area (15° great circle arc from TC center) is identified from the TRMM-3B42 precipitation data for every 6-h interval of the best-track data. The maximum potential range of TC rainfall area is set large

enough to contain most of the rain cells that are potentially associated with the TC (Jiang et al. 2011; Lin et al. 2015). Herein, a rain cell is defined as adjacent grid boxes showing the precipitation rate in excess of 0.5 mm hr^{-1} (Jiang et al. 2011; Lin et al. 2015). Most of the previous studies considered that a rain cell is related to the TC if the distance between the rain cell and TC center is less than a specific value (e.g., 500 km in Jiang et al. 2011; Matyas 2013, 2014). However, such a definition of TC rainfall area can be affected sensitively by the criterion of the distance from the TC center. If the distance criterion is too small, TC rainfall area will be underestimated (e.g., Supertyphoon Tip in 1974; Merrill 1984). On the other hand, TC rainfall area will be overestimated if the distance criterion is too large, because rain cells that are irrelevant to the TC can be included in TC rainfall area.

This study defines the TC rainfall area using two different criteria of the distance from the TC center. If the minimum distance from a rain cell to the TC center is less than the inner-zone criterion (300 km), the rain cell is considered as the TC rain cell. For a rain cell satisfying the outer-zone criterion (i.e., the minimum distance from the TC center is in the range of 300–900 km), it is not appropriate to classify the rain cell simply according to the distance from the TC center because mesoscale convective systems other than TC may exist in the outer zone. To distinguish effectively the TC rain cells from non-TC rain cells in the outer zone, rain cells are divided into convective and stratiform cells. A rain cell is classified as a convective cell if its maximum precipitation exceeds 5 mm hr^{-1} . This threshold value is similar to precipitation observed in convective cells of TC rainbands (Willoughby 1988; Houze 2010) and corresponds

FIG. 2. Schematic diagram of the algorithm estimating TC rainfall area.

to a heavy rain threshold for TCs in [Jiang et al. \(2011\)](#). If the cell does not meet this criterion, it is classified as a stratiform cell. After classification, each convective cell is traced for every 6 h during 4 days (i.e., 2 days forward and 2 days backward). During the tracing process, all convective cells that overlap with the traced cell are identified in the next time step and traced continuously, as the traced cell can merge with other cells or be divided into smaller cells. The traced cell is classified as a TC rain cell if the minimum distance between the overlapping cells and the TC center is less than 900 km for more than 2 continuous days. For stratiform cells, a rain cell is classified as the TC rain cell if it is located in the outer zone. Stratiform cells in the outer zone are not traced because they are usually very small and scattered, and last for only a short period of time. In addition, stratiform cells are found to account for a small part of the total TC rainfall area (about 9% on average). Finally, the TC rainfall area is defined as the total area of all TC rain cells passing the algorithm.

In this study, rainfall asymmetry is also defined by applying the Fourier transform to rainfall area (e.g., [Lonfat et al. 2004](#); [Chen et al. 2006](#)). TC rainfall area is divided into 36 azimuthal bins and decomposed into wave components in azimuthal direction. The rainfall asymmetry is

defined as the ratio of the amplitude of each wavenumber to that of wavenumber zero. This study focuses on the wavenumber-1 asymmetry, which explains most of the variability of the total rainfall area (40.1%).

3. Relationship between TC rainfall area and environmental conditions

[Figure 3](#) shows a sample of TC rainfall area estimated from the TRMM-3B42 precipitation data. The algorithm developed in this study reasonably captures TC rainfall area located at a remote region as well as near the center of the TC ([Figs. 3f–j](#)). In addition, the algorithms using the double-distance criteria (DDC; 300 and 900 km), which are adopted in this study, and single-distance criterion (SDC; 500 km), which is applied in the most of previous studies (e.g., [Jiang et al. 2011](#); [Matyas 2013, 2014](#)), generally show similar results ([Figs. 3k–o](#)). However, the TC rainfall area calculated by the latter may significantly change according to the distance criterion. For example, the rainfall area expending north-eastward is not included in the TC rainfall area of Tropical Storm Kammuri at 0600 UTC 27 September 2014 when the SDC is used ([Fig. 3n](#)). Thus, the rainfall area calculated using the SDC is underestimated by

FIG. 3. Rainfall area of TS Kammuri from 1200 UTC 26 Sep 2014 to 1200 UTC 27 Sep 2014. The left, middle, and right columns show the (a)–(e) raw precipitation data from the TRMM-3B42 data, (f)–(g) TC rainfall area estimated by applying DDC (300 and 900 km; red and black circles, respectively), and (k)–(o) TC rainfall area estimated by applying SDC (500 km; black circle), respectively.

TABLE 1. Rainfall area (unit: 10^5 km^2) of the TS Kammuri and surrounding environmental conditions from 1200 UTC 26 Sep 2014 to 1200 UTC 27 Sep 2014.

Time	Rainfall area (10^5 km^2)	SST ($^{\circ}\text{C}$)	Eastward-moving speed (m s^{-1})	Northward-moving speed (m s^{-1})	Eastward vertical wind shear (m s^{-1})	Northward vertical wind shear (m s^{-1})
1200 UTC 26 Sep 2014	6.36	29.3	-1.9	3.9	1.6	1.1
1800 UTC 26 Sep 2014	7.99	29.2	-2.1	4.6	3.2	1.2
0000 UTC 27 Sep 2014	11.10	28.6	-1.9	6.4	5.1	1.7
0600 UTC 27 Sep 2014	9.60	27.7	-1.6	6.2	9.0	3.5
1200 UTC 27 Sep 2014	10.05	27.3	-0.5	4.4	10.5	3.0

about 60% compared to that using the DDC at that time (Figs. 3i,n). Such underestimation of TC rainfall area using the SDC appears frequently in other TC cases, which makes the TC rainfall area using the SDC smaller than that using the DDC by about 20% on average (significant at the 95% confidence level). This study tested both algorithms, but only the results of applying the DDC algorithm are shown since the overall results are similar; the correlation coefficient between the TC rainfall areas of the two algorithms is 0.83.

When Tropical Storm (TS) Kammuri (2014) moves to the subtropics, the rainfall area expands northeastward and becomes asymmetric (Figs. 3f-j). The environmental conditions around Kammuri also change significantly (Table 1). As Kammuri generally moves in the north direction with steady speed, SST under the TC decreases with time. It is notable that the rainfall area of Kammuri increases although SST under the TC decreases. On the other hand, environmental vertical wind shear appears in the east-northeast direction and gets stronger with time, which implies the fluctuation of the TC rainfall area can be related to the change in environmental circulation. In the following, we investigate the general relationship between the TC rainfall area and each environmental condition for all TC cases in the subtropics.

In the subtropics, the global-mean TC rainfall area is found to be $4.75 \times 10^5 \text{ km}^2$, which corresponds to the area of circle with a radius of 389 km. In addition, TC rainfall areas are generally large in order of the WNP, SP, SI, and NA (Table 2); these are similar to geographic distributions of TC wind size (Knaff et al. 2014; Chan and Chan 2015; Chavas et al. 2016). Figure 4 shows the variations of TC rainfall area according to environmental conditions in the global and individual ocean basins. Globally, TC rainfall area in the subtropics increases with TC intensity (i.e., maximum wind speed), but its growth rate slows down as TC intensity increases, which is similar to the relationship between TC wind size and intensity (Chavas et al. 2016). Note that TC rainfall area in the subtropics shows insignificant variations according to SST but clearly increases with moving speed and vertical wind shear. These features are commonly observed in individual ocean basins, although their

sample numbers and mean values of TC rainfall area are different (right column in Fig. 4). In particular, TC rainfall area increases with decreasing SST and increasing moving speed and vertical wind shear in the WNP and the SP, which is similar to the case of Kammuri. If TC rainfall area is dominantly controlled by SST, the inverse relationship between TC rainfall area and SST would be hard to appear. Thus, it is suggested that TC rainfall area in the subtropics is more controlled by dynamic environmental conditions (i.e., moving speed and vertical wind shear) than thermodynamic ones (i.e., SST). In contrast, TC rainfall area in the tropics is primarily controlled by SST, but not by moving speed and vertical wind shear (gray color in Fig. 4), which is consistent with the findings of Lin et al. (2015).

The different variations of TC rainfall area between the subtropics and the tropics are likely attributed to the different environmental conditions between these two regions. TCs in the tropics are exposed to significantly higher SSTs than those in the subtropics regardless of moving speed and vertical wind shear (Fig. 5). In addition, SST in the tropics shows insignificant variations according to moving speed and decreases slowly with vertical wind shear (gray color, Fig. 5), while SST decreases rapidly with moving speed and vertical wind shear in the subtropics (black color, Fig. 5). Summing up, TCs in the subtropics generally meet cooler SSTs with stronger environmental flows compared to those in the tropics (Table 3). Because SST is the major energy source of TCs, sufficiently warm SST (usually above 26° – 27°C) is a necessary condition for TC development (Palmén 1948; Gray 1968). A TC also can resist the influence of environmental flows when it is strong enough

TABLE 2. Statistics of TC rainfall area (unit: 10^5 km^2) in the subtropics for global oceans, WNP, NA, SI, and SP.

	25%	Median	75%	Mean	Std dev
Global	2.22	3.89	6.66	4.75	0.69
WNP	3.18	5.44	8.12	5.98	0.57
NA	1.59	2.77	4.36	3.34	0.71
SI	1.80	3.26	5.21	3.72	0.63
SP	2.55	4.65	8.37	5.71	0.72

FIG. 4. Rainfall area distributions with varying (a),(e) max wind speed, (b),(f) SST, (c),(g) moving speed, and (d),(h) vertical wind shear. Left and right columns present the analysis result for global and individual subtropical ocean basins, respectively. Dots and error bars denote the mean and 95% confidence interval of the mean, respectively. Only bins with sample numbers larger than 50 are presented here.

FIG. 5. Distributions of SST with varying (a) moving speed and (b) vertical wind shear in the subtropics and the tropics of global oceans. Dots and error bars denote the mean and 95% confidence interval of the mean, respectively. Only bins with sample numbers larger than 50 are presented here.

(e.g., Jones 1995; Wong and Chan 2004). Thus, the sensitivity of TC rainfall area to moving speed and vertical wind shear may increase in cool SST conditions. Indeed, TC rainfall areas in the subtropics and the tropics show similar variations according to moving speed and vertical wind shear (Figs. 4c,d) when SST is cooler than 27°–28°C (Fig. 5).

At this point, it is necessary to discuss how TC moving speed and vertical wind shear affect TC rainfall area. In the subtropics, TCs show a distinct rainfall asymmetry

TABLE 3. Avg environmental conditions in the subtropics and the tropics. All environmental conditions in the two regions show significant difference at the 99% confidence level.

	SST (°C)	Moving speed (m s ⁻¹)	Vertical wind shear (m s ⁻¹)
Subtropics	26.4	6.0	10.8
Tropics	28.3	5.5	6.8

regardless of ocean basin (Fig. 6). In particular, TC rainfall area expands northeastward and southeastward in the Northern (Figs. 6a,b) and the Southern Hemisphere (Figs. 6c,d), respectively. It is also notable that the direction of the rainfall asymmetry is located between the directions of TC motion (blue arrows in Fig. 6) and vertical wind shear (red arrows in Fig. 6). This result is consistent with previous studies showing that TC rainfall is enhanced asymmetrically at the front-right (front-left) side of TC motion and the downshear-left (downshear-right) side in the Northern (Southern) Hemisphere (Corbosiero and Molinari 2002, 2003; Chen et al. 2006). The magnitude of rainfall asymmetry increases with TC moving speed and vertical wind shear (Figs. 7a and 7b, respectively). Particularly, rainfall asymmetry doubles when vertical wind shear increases

FIG. 6. Avg TC rainfall area in azimuthal bins (unit: 10^4 km^2) in the subtropics of (a) WNP, (b) NA, (c) SI, and (d) SP. Blue and red arrows indicate the mean direction of TC motion and vertical wind shear, respectively. Dots and error bars denote the mean and 95% confidence interval of the mean, respectively.

FIG. 7. Rainfall asymmetry distributions of subtropical TCs in global and individual ocean basins with varying (a) moving speed and (b) vertical wind shear. (c) The relationship between rainfall area and asymmetry. Dots and error bars denote the mean and 95% confidence interval of the mean, respectively. Only bins with sample numbers larger than 50 are presented here.

TABLE 4. Avg environmental conditions in the individual subtropical ocean basins.

	SST ($^{\circ}\text{C}$)	Moving speed (m s^{-1})	Vertical wind shear (m s^{-1})
WNP	27.1	6.4	9.1
NA	27.2	4.9	8.8
SI	24.4	5.9	15.4
SP	23.9	8.3	16.7

from 0 to 26 m s^{-1} . The rainfall asymmetry in the Southern Hemisphere is significantly larger than that in the Northern Hemisphere, which is also related to the stronger vertical wind shear in the Southern Hemisphere than in the Northern Hemisphere (Table 4). Changes in rainfall asymmetry due to TC moving speed are relatively small compared to those induced by vertical wind shear. In addition, there is no clear increase in rainfall asymmetry when TC moving speed is low ($< 5 \text{ m s}^{-1}$) (Fig. 7a). These results may imply that vertical wind shear develops asymmetric rainfall more efficiently than TC moving speed does, which is similar to the results of Chen et al. (2006). Last, the relationship between rainfall area and asymmetries also shows that TC rainfall area tends to increase (by up to a factor of 2) with rainfall asymmetry (Fig. 7c), and the increasing rate levels off above certain asymmetry values. The rainfall area generally increases in the rainfall asymmetry range (0.5–1.4) appearing in Figs. 7a and 7b. Therefore, higher TC moving speed and vertical wind shear are likely to enlarge TC rainfall area by encouraging asymmetric rainfall structure. All the results above are consistently found in each ocean basin.

4. Summary and discussion

In this study, the relationship between TC rainfall area and environmental conditions in the subtropics is investigated over global oceans using the TRMM-3B42 precipitation data. The TC rainfall area in the subtropics is found to be significantly influenced by TC motion and vertical wind shear, but not by SST. This result is in contrast to the fact that TC rainfall area and wind size is mainly controlled by SST in the tropics (Lin et al. 2015; Chavas et al. 2016). A number of previous studies have pointed out that TC motion and vertical wind shear can induce asymmetric TC rainfall (e.g., Frank and Ritchie 1999, 2001; Corbosiero and Molinari 2002, 2003; Chen et al. 2006). Based on the results of previous studies, we investigated the relationship between the environmental flow, rainfall asymmetry, and TC rainfall area. As a result, we found that higher TC moving speed and larger vertical wind shear contribute to increases in TC rainfall area by developing asymmetric rainfall structure.

An extratropical transition can contribute to the tight relationship between the environmental flow, rainfall asymmetry, and TC rainfall area. In the extratropical transition, a TC may get energy mainly from baroclinic instability of the environment rather than cool ocean surface in the subtropics (e.g., [Harr and Elsberry 2000](#); [Harr et al. 2000](#); [Jones et al. 2003](#)). Thus, SST would not be the primary factor modulating TC rainfall area in the subtropics. In addition, TC rainfall area and maximum wind speed show a positive relationship in the subtropics, unlike the tropics, which can be related to a rapid intensification that appears frequently with the extratropical transition (e.g., [Klein et al. 2000](#); [Ritchie and Elsberry 2003](#)). The overall results suggest the importance of local environmental conditions, such as strong baroclinity and environmental flows in the subtropics and warm ocean surface in the tropics, in determining TC rainfall area. Thus, various environmental conditions and related mechanisms controlling TC rainfall area must be considered in order to improve the forecast of TC rainfall area.

Furthermore, it is necessary to understand quantitatively the variation of TC rainfall area due to the changes in environmental conditions for an accurate prediction of TC rainfall area. In this study, however, it is difficult to quantify the contribution of each environmental condition. For example, the influence of TC motion and vertical wind shear on TC rainfall area appears simultaneously and cannot be easily evaluated separately. Meanwhile, numerical models can simulate an idealized TC in a controlled environmental condition, which makes it possible to examine quantitatively how TC rainfall responds to environmental conditions. Therefore, planned future work includes further study of numerical modeling experiments on the relationships between TC rainfall area and various environmental conditions.

Acknowledgments. This study was funded by the Korea Ministry of Environment as “Climate Change Correspondence Program.” Chan was supported by the Research Grants Council of Hong Kong (Grant CityU 11300214). Most of the works of Park were conducted at the Korea Adaptation Center for Climate Change, Korea Environment Institute, Republic of Korea. We thank the three anonymous reviewers for valuable comments that improved and clarified this manuscript.

REFERENCES

- Bender, M. A., 1997: The effect of relative flow on the asymmetric structure in the interior of hurricanes. *J. Atmos. Sci.*, **54**, 703–724, [https://doi.org/10.1175/1520-0469\(1997\)054<0703:TEORFO>2.0.CO;2](https://doi.org/10.1175/1520-0469(1997)054<0703:TEORFO>2.0.CO;2).
- Bosart, L. F., W. E. Bracken, J. Molinari, C. S. Velden, and P. G. Black, 2000: Environmental influences on the rapid intensification of Hurricane Opal (1995) over the Gulf of Mexico. *Mon. Wea. Rev.*, **128**, 322–352, [https://doi.org/10.1175/1520-0493\(2000\)128<0322:EIOTRI>2.0.CO;2](https://doi.org/10.1175/1520-0493(2000)128<0322:EIOTRI>2.0.CO;2).
- Bosilovich, M. G., and Coauthors, 2015: MERRA-2: Initial evaluation of the climate. NASA Tech. Rep. Series on Global Modeling and Data Assimilation, Vol. 43, NASA/TM-2015-104606, 139 pp.
- Cecil, D. J., 2007: Satellite-derived rain rates in vertically sheared tropical cyclones. *Geophys. Res. Lett.*, **34**, L02811, <https://doi.org/10.1029/2006GL027942>.
- Chan, K. T. F., and J. C. L. Chan, 2012: Size and strength of tropical cyclones as inferred from QuikSCAT data. *Mon. Wea. Rev.*, **140**, 811–824, <https://doi.org/10.1175/MWR-D-10-05062.1>.
- , and —, 2015: Global climatology of tropical cyclone size as inferred from QuikSCAT data. *Int. J. Climatol.*, **35**, 4843–4848, <https://doi.org/10.1002/joc.4307>.
- Changnon, S. A., 2008: Assessment of flood losses in the United States. *J. Contemp. Water Res. Educ.*, **138**, 38–44, <https://doi.org/10.1111/j.1936-704X.2008.00007.x>.
- Chavas, D. R., N. Lin, W. Dong, and Y. Lin, 2016: Observed tropical cyclone size revisited. *J. Climate*, **29**, 2923–2939, <https://doi.org/10.1175/JCLI-D-15-0731.1>.
- Chen, S. S., J. A. Knaff, and F. D. Marks Jr., 2006: Effects of vertical wind shear and storm motion on tropical cyclone rainfall asymmetries deduced from TRMM. *Mon. Wea. Rev.*, **134**, 3190–3208, <https://doi.org/10.1175/MWR3245.1>.
- Chen, Y., and M. K. Yau, 2003: Asymmetric structures in a simulated landfalling hurricane. *J. Atmos. Sci.*, **60**, 2294–2312, [https://doi.org/10.1175/1520-0469\(2003\)060<2294:ASIASL>2.0.CO;2](https://doi.org/10.1175/1520-0469(2003)060<2294:ASIASL>2.0.CO;2).
- Corbosiero, K. L., and J. Molinari, 2002: The effects of vertical wind shear on the distribution of convection in tropical cyclones. *Mon. Wea. Rev.*, **130**, 2110–2123, [https://doi.org/10.1175/1520-0493\(2002\)130<2110:TEOVWS>2.0.CO;2](https://doi.org/10.1175/1520-0493(2002)130<2110:TEOVWS>2.0.CO;2).
- , and —, 2003: The relationship between storm motion, vertical wind shear, and convective asymmetries in tropical cyclones. *J. Atmos. Sci.*, **60**, 366–376, [https://doi.org/10.1175/1520-0469\(2003\)060<0366:TRBSMV>2.0.CO;2](https://doi.org/10.1175/1520-0469(2003)060<0366:TRBSMV>2.0.CO;2).
- Czajkowski, J., K. Simmons, and D. Sutter, 2011: An analysis of coastal and inland fatalities in landfalling US hurricanes. *Nat. Hazards*, **59**, 1513–1531, <https://doi.org/10.1007/s11069-011-9849-x>.
- , G. Villarini, M. Montgomery, E. Michel-Kerjan, and R. Goska, 2017: Assessing current and future freshwater flood risk from North Atlantic tropical cyclones via insurance claims. *Sci. Rep.*, **7**, 41609, <https://doi.org/10.1038/srep41609>.
- DeMaria, M., 1996: The effect of vertical shear on tropical cyclone intensity change. *J. Atmos. Sci.*, **53**, 2076–2088, [https://doi.org/10.1175/1520-0469\(1996\)053<2076:TEOVSO>2.0.CO;2](https://doi.org/10.1175/1520-0469(1996)053<2076:TEOVSO>2.0.CO;2).
- , and J. Kaplan, 1994: A Statistical Hurricane Intensity Prediction Scheme (SHIPS) for the Atlantic basin. *Wea. Forecasting*, **9**, 209–220, [https://doi.org/10.1175/1520-0434\(1994\)009<0209:ASHIPS>2.0.CO;2](https://doi.org/10.1175/1520-0434(1994)009<0209:ASHIPS>2.0.CO;2).
- , M. Mainelli, L. K. Shay, J. A. Knaff, and J. Kaplan, 2005: Further improvements to the Statistical Hurricane Intensity Prediction Scheme (SHIPS). *Wea. Forecasting*, **20**, 531–543, <https://doi.org/10.1175/WAF862.1>.
- Emanuel, K. A., 1986: An air–sea interaction theory for tropical cyclones. Part I: Steady-state maintenance. *J. Atmos. Sci.*, **43**, 585–605, [https://doi.org/10.1175/1520-0469\(1986\)043<0585:AASITF>2.0.CO;2](https://doi.org/10.1175/1520-0469(1986)043<0585:AASITF>2.0.CO;2).
- , 1995a: Sensitivity of tropical cyclones to surface exchange coefficients and a revised steady-state model incorporating

- eye dynamics. *J. Atmos. Sci.*, **52**, 3969–3976, [https://doi.org/10.1175/1520-0469\(1995\)052<3969:SOTCTS>2.0.CO;2](https://doi.org/10.1175/1520-0469(1995)052<3969:SOTCTS>2.0.CO;2).
- , 1995b: The behavior of a simple hurricane model using a convective scheme based on subcloud-layer entropy equilibrium. *J. Atmos. Sci.*, **52**, 3960–3968, [https://doi.org/10.1175/1520-0469\(1995\)052<3960:TBOASH>2.0.CO;2](https://doi.org/10.1175/1520-0469(1995)052<3960:TBOASH>2.0.CO;2).
- Frank, W. M., and E. A. Ritchie, 1999: Effects of environmental flow upon tropical cyclone structure. *Mon. Wea. Rev.*, **127**, 2044–2061, [https://doi.org/10.1175/1520-0493\(1999\)127<2044:EOEFUT>2.0.CO;2](https://doi.org/10.1175/1520-0493(1999)127<2044:EOEFUT>2.0.CO;2).
- , and —, 2001: Effects of vertical wind shear on the intensity and structure of numerically simulated hurricanes. *Mon. Wea. Rev.*, **129**, 2249–2269, [https://doi.org/10.1175/1520-0493\(2001\)129<2249:EOVWSO>2.0.CO;2](https://doi.org/10.1175/1520-0493(2001)129<2249:EOVWSO>2.0.CO;2).
- Gray, W. M., 1968: Global view of the origin of tropical disturbances and storms. *Mon. Wea. Rev.*, **96**, 669–700, [https://doi.org/10.1175/1520-0493\(1968\)096<0669:GVOTOO>2.0.CO;2](https://doi.org/10.1175/1520-0493(1968)096<0669:GVOTOO>2.0.CO;2).
- Hanley, D., J. Molinari, and D. Keyser, 2001: A composite study of the interactions between tropical cyclones and upper-tropospheric troughs. *Mon. Wea. Rev.*, **129**, 2570–2584, [https://doi.org/10.1175/1520-0493\(2001\)129<2570:ACSOTI>2.0.CO;2](https://doi.org/10.1175/1520-0493(2001)129<2570:ACSOTI>2.0.CO;2).
- Harr, P. A., and R. L. Elsberry, 2000: Extratropical transition of tropical cyclones over the western North Pacific. Part I: Evolution of structural characteristics during the transition process. *Mon. Wea. Rev.*, **128**, 2613–2633, [https://doi.org/10.1175/1520-0493\(2000\)128<2613:ETOTCO>2.0.CO;2](https://doi.org/10.1175/1520-0493(2000)128<2613:ETOTCO>2.0.CO;2).
- , —, and T. F. Hogan, 2000: Extratropical transition of tropical cyclones over the western North Pacific. Part II: The impact of midlatitude circulation characteristics. *Mon. Wea. Rev.*, **128**, 2634–2653, [https://doi.org/10.1175/1520-0493\(2000\)128<2634:ETOTCO>2.0.CO;2](https://doi.org/10.1175/1520-0493(2000)128<2634:ETOTCO>2.0.CO;2).
- Hill, K. A., and G. M. Lackmann, 2009: Influence of environmental humidity on tropical cyclone size. *Mon. Wea. Rev.*, **137**, 3294–3315, <https://doi.org/10.1175/2009MWR2679.1>.
- Houze, R. A., Jr., 2010: Clouds in tropical cyclones. *Mon. Wea. Rev.*, **138**, 293–344, <https://doi.org/10.1175/2009MWR2989.1>.
- Huffman, G. J., and Coauthors, 2007: The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. *J. Hydrometeorol.*, **8**, 38–55, <https://doi.org/10.1175/JHM560.1>.
- Jiang, H., and E. J. Zipser, 2010: Contribution of tropical cyclones to the global precipitation from eight seasons of TRMM data: Regional, seasonal, and interannual variations. *J. Climate*, **23**, 1526–1543, <https://doi.org/10.1175/2009JCLI3303.1>.
- , J. B. Halverson, and E. J. Zipser, 2008: Influence of environmental moisture on TRMM-derived tropical cyclone precipitation over land and ocean. *Geophys. Res. Lett.*, **35**, L17806, <https://doi.org/10.1029/2008GL034658>.
- , C. Liu, and E. J. Zipser, 2011: A TRMM-based tropical cyclone cloud and precipitation feature database. *J. Appl. Meteor. Climatol.*, **50**, 1255–1274, <https://doi.org/10.1175/2011JAMC2662.1>.
- Jones, S. C., 1995: The evolution of vortices in vertical shear. I: Initially barotropic vortices. *Quart. J. Roy. Meteor. Soc.*, **121**, 821–851, <https://doi.org/10.1002/qj.49712152406>.
- , and Coauthors, 2003: The extratropical transition of tropical cyclones: Forecast challenges, current understanding, and future directions. *Wea. Forecasting*, **18**, 1052–1092, [https://doi.org/10.1175/1520-0434\(2003\)018<1052:TETOTC>2.0.CO;2](https://doi.org/10.1175/1520-0434(2003)018<1052:TETOTC>2.0.CO;2).
- Kimball, S. K., 2008: Structure and evolution of rainfall in numerically simulated landfalling hurricanes. *Mon. Wea. Rev.*, **136**, 3822–3847, <https://doi.org/10.1175/2008MWR2304.1>.
- Klein, P. M., P. A. Harr, and R. L. Elsberry, 2000: Extratropical transition of western North Pacific tropical cyclones: An overview and conceptual model of the transformation stage. *Wea. Forecasting*, **15**, 373–395, [https://doi.org/10.1175/1520-0434\(2000\)015<0373:ETOWNP>2.0.CO;2](https://doi.org/10.1175/1520-0434(2000)015<0373:ETOWNP>2.0.CO;2).
- Knaff, J. A., S. P. Longmore, and D. A. Molenaar, 2014: An objective satellite-based tropical cyclone size climatology. *J. Climate*, **27**, 455–476, <https://doi.org/10.1175/JCLI-D-13-00096.1>.
- Knapp, K. R., M. C. Kruk, D. H. Levinson, H. J. Diamond, and C. J. Neumann, 2010: The International Best Track Archive for Climate Stewardship (IBTrACS): Unifying tropical cyclone data. *Bull. Amer. Meteor. Soc.*, **91**, 363–376, <https://doi.org/10.1175/2009BAMS2755.1>.
- Krishnamurti, T. N., S. Pattnaik, M. K. Biswas, E. Bensman, M. Kramer, N. Surgi, and T. S. V. V. Kumar, 2010: Hurricane forecasts with a mesoscale suite of models. *Tellus*, **62A**, 633–646, <https://doi.org/10.1111/j.1600-0870.2010.00469.x>.
- , M. K. Biswas, B. P. Mackey, R. G. Ellingson, and P. H. Ruscher, 2011: Hurricane forecasts using a suite of large-scale models. *Tellus*, **63A**, 727–745, <https://doi.org/10.1111/j.1600-0870.2011.00519.x>.
- Lin, Y., M. Zhao, and M. Zhang, 2015: Tropical cyclone rainfall area controlled by relative sea surface temperature. *Nat. Commun.*, **6**, 6591, <https://doi.org/10.1038/ncomms7591>.
- Lonfat, M., F. D. Marks Jr., and S. S. Chen, 2004: Precipitation distribution in tropical cyclones using the Tropical Rainfall Measuring Mission (TRMM) microwave imager: A global perspective. *Mon. Wea. Rev.*, **132**, 1645–1660, [https://doi.org/10.1175/1520-0493\(2004\)132<1645:PDITCU>2.0.CO;2](https://doi.org/10.1175/1520-0493(2004)132<1645:PDITCU>2.0.CO;2).
- , R. Rogers, T. Marchok, and F. D. Marks Jr., 2007: A parametric model for predicting hurricane rainfall. *Mon. Wea. Rev.*, **135**, 3086–3097, <https://doi.org/10.1175/MWR3433.1>.
- Matyas, C. J., 2010: Associations between the size of hurricane rain fields at landfall and their surrounding environments. *Meteor. Atmos. Phys.*, **106**, 135–148, <https://doi.org/10.1007/s00703-009-0056-1>.
- , 2013: Processes influencing rain-field growth and decay after tropical cyclone landfall in the United States. *J. Appl. Meteor. Climatol.*, **52**, 1085–1096, <https://doi.org/10.1175/JAMC-D-12-0153.1>.
- , 2014: Conditions associated with large rain-field areas for tropical cyclones landfalling over Florida. *Phys. Geogr.*, **35**, 93–106, <https://doi.org/10.1080/02723646.2014.893476>.
- Merrill, R. T., 1984: A comparison of large and small tropical cyclones. *Mon. Wea. Rev.*, **112**, 1408–1418, [https://doi.org/10.1175/1520-0493\(1984\)112<1408:ACOLAS>2.0.CO;2](https://doi.org/10.1175/1520-0493(1984)112<1408:ACOLAS>2.0.CO;2).
- Palmén, E., 1948: On the formation and structure of tropical hurricanes. *Geophysica*, **3**, 26–38.
- Park, D.-S. R., C.-H. Ho, C. C. Nam, and H.-S. Kim, 2015: Evidence of reduced vulnerability to tropical cyclones in the Republic of Korea. *Environ. Res. Lett.*, **10**, 054003, <https://doi.org/10.1088/1748-9326/10/5/054003>.
- , —, J. Kim, K. Kang, and C. C. Nam, 2016: Highlighting socioeconomic damages caused by weakened tropical cyclones in the Republic of Korea. *Nat. Hazards*, **82**, 1301–1315, <https://doi.org/10.1007/s11069-016-2244-x>.
- Peng, M. S., B.-F. Jeng, and R. T. Williams, 1999: A numerical study on tropical cyclone intensification. Part I: Beta effect and mean flow effect. *J. Atmos. Sci.*, **56**, 1404–1423, [https://doi.org/10.1175/1520-0469\(1999\)056<1404:ANSOTC>2.0.CO;2](https://doi.org/10.1175/1520-0469(1999)056<1404:ANSOTC>2.0.CO;2).
- Rappaport, E. N., 2014: Fatalities in the United States from Atlantic tropical cyclones: New data and interpretation. *Bull. Amer. Meteor. Soc.*, **95**, 341–346, <https://doi.org/10.1175/BAMS-D-12-00074.1>.
- Reynolds, R. W., N. A. Rayner, T. M. Smith, D. C. Stokes, and W. Wang, 2002: An improved in situ and satellite SST analysis

- for climate. *J. Climate*, **15**, 1609–1625, [https://doi.org/10.1175/1520-0442\(2002\)015<1609:AIISAS>2.0.CO;2](https://doi.org/10.1175/1520-0442(2002)015<1609:AIISAS>2.0.CO;2).
- Ritchie, E. A., and R. L. Elsberry, 2003: Simulations of the extratropical transition of tropical cyclones: Contributions by the midlatitude upper-level trough to reintensification. *Mon. Wea. Rev.*, **131**, 2112–2128, [https://doi.org/10.1175/1520-0493\(2003\)131<2112:SOTETO>2.0.CO;2](https://doi.org/10.1175/1520-0493(2003)131<2112:SOTETO>2.0.CO;2).
- Sampson, C. R., and A. J. Schrader, 2000: The Automated Tropical Cyclone Forecasting System (version 3.2). *Bull. Amer. Meteor. Soc.*, **81**, 1231–1240, [https://doi.org/10.1175/1520-0477\(2000\)081<1231:TATCFS>2.3.CO;2](https://doi.org/10.1175/1520-0477(2000)081<1231:TATCFS>2.3.CO;2).
- Shapiro, L. J., 1983: The asymmetric boundary layer flow under a translating hurricane. *J. Atmos. Sci.*, **40**, 1984–1998, [https://doi.org/10.1175/1520-0469\(1983\)040<1984:TABLFU>2.0.CO;2](https://doi.org/10.1175/1520-0469(1983)040<1984:TABLFU>2.0.CO;2).
- Willoughby, H. E., 1988: The dynamics of the tropical hurricane core. *Aust. Meteor. Mag.*, **36**, 183–191.
- Wong, M. L. M., and J. C. L. Chan, 2004: Tropical cyclone intensity in vertical wind shear. *J. Atmos. Sci.*, **61**, 1859–1876, [https://doi.org/10.1175/1520-0469\(2004\)061<1859:TCHVW>2.0.CO;2](https://doi.org/10.1175/1520-0469(2004)061<1859:TCHVW>2.0.CO;2).
- Xu, W., H. Jiang, and X. Kang, 2014: Rainfall asymmetries of tropical cyclones prior to, during, and after making landfall in south China and southeast United States. *Atmos. Res.*, **139**, 18–26, <https://doi.org/10.1016/j.atmosres.2013.12.015>.
- Yu, H., P. Chen, Q. Li, and B. Tang, 2013: Current capability of operational numerical models in predicting tropical cyclone intensity in the western North Pacific. *Wea. Forecasting*, **28**, 353–367, <https://doi.org/10.1175/WAF-D-11-00100.1>.