Improved Climatology of Tropical Cyclone Precipitation from Satellite Passive Microwave Measurements

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Abstract: An accurate precipitation climatology is presented for tropical depression (TD), tropical storm (TS), and tropical cyclone (TC) occurrences over oceans using recently released, consistent, and high-quality precipitation datasets from all passive microwave sensors covering 1998–2012 along with the Automated Rotational Center Hurricane Eye Retrieval (ARCHER)-based TC center positions. Impacts with respect to the direction of both TC movement and the 200–850-hPa wind shear on the spatial distributions of TC precipitation are analyzed. The TC eyewall contraction process during its intensification is noted by a decrease in the radius of maximum rain rate with an increase in TC intensity. For global TCs, the maximum rain rate with respect to the direction of TC movement is located in the down-motion quadrants for TD, TS, and category-1–3 TCs, and in a concentric pattern for category-4/5 TCs. A consistent maximum TC precipitation with respect to the direction of the 200–850-hPa wind shear is shown in the downshear left quadrant (DSLO). With respect to direction of TC movement, spatial patterns of TC precipitation vary with basins and show different features for weak and strong storms. The maximum rain rate is always located in DSLO for all TC categories and basins, except the Southern Hemisphere basin where it is in the downshear right quadrant. This study not only confirms previously published results on TC precipitation distributions relative to vertical wind shear direction, but also provides a detailed distribution for each TC category and TS, while TD storms display an enhanced rainfall rate ahead of the downshear quadrants.

Keywords: Precipitation; Tropical cyclones; Hurricanes/typhoons; Satellite observations

1. Introduction

Tropical cyclones (TCs) can be among the most severe and destructive weather systems, leading to the loss of lives, property damage, and other societal impacts. TCs are classified into five intensity categories (1–5, with 5 being the most intense) depending on the Saffir–Simpson hurricane wind scale, in addition to tropical depression (TD) and tropical storm (TS) designations, depending on the National Oceanic and Atmospheric Administration (NOAA) National Hurricane Center (NHC) Saffir–Simpson Hurricane Scale (NOAA 2010) and the World Meteorological Organization (WMO) Regional Association IV Hurricane Operational Plan 2015 (WMO 2015). Category-3–5 TCs are also considered to be major hurricanes in the Atlantic and North Pacific Ocean basins. Some of the costliest U.S. hurricanes occurred in 2017 and 2018 (Amadeo 2020). For example, Hurricane Harvey (category 4) made landfall in Texas on 25 August 2017, resulting in 88 deaths and an estimated $125 billion in damages. An estimated death toll of 4645 and costs of $90 billion were caused by Hurricane Maria (category 5). TCs are often associated with a tremendous amount of rainfall in a short period of time, frequently leading to flash floods. Flooding is one of the major factors in human fatalities based on weather-related fatality and injury statistics from the NOAA National Weather Service (NOAA 2020). Understanding the characteristics of TC precipitation and geographic variability is important for improving TC precipitation forecasts and mitigating the impacts from incoming storms.

Heavy rainfall from TCs is mostly associated with spiral convective areas, which exhibit an asymmetrical distribution of TC precipitation (Rogers et al. 2009; Yang and Cossuth 2016). Improved TC rainfall prediction will provide more accurate information to local/regional decision-making authorities to more effectively prepare for and mitigate the devastating impacts of an approaching TC. Results within the published literature regarding TC precipitation intensity and distribution are mostly based on less accurate and limited rainfall datasets. TC precipitation distribution is affected by many factors, such as topography, advection of planetary vorticity, friction-induced boundary layer convergence, and vertical wind shear (Bender 1997; Corbosiero and Molinari 2002; Geerts et al. 2000; Lin et al. 2002; Chiao and Lin 2003; Smith and Barstad 2004; Lonfat et al. 2004, 2007; Marks et al. 2002; Chen et al. 2006; Cecil 2007; Langoussis and Veneziano 2009). Vertical wind shear is normally defined as the difference of the averaged winds within 200–800-km radii from a TC center between 200 and 850 hPa (Knaff et al. 2005). The impact of topography on TC precipitation is mostly due to enhanced upward motion, mechanically forced by topography. The orographic modulation could also reduce rainfall where it induces downslope flow. There are many factors associated with this process, such as the structure and intensity of TC winds, boundary layer conditions, and the incidence angle of the flow relative to the barrier. However, the degree of topographic ascent is the most important factor in enhancing TC rainfall (Alpert and Shafir...
Some well-known cases of TC rainfall are over the mountainous areas of Taiwan, which is frequently in the path of western Pacific (WP) TCs. Lonfat et al. (2004) presented a climatology of TC precipitation distribution using an early version (V5) of three years (1998–2000) of Tropical Rainfall Measuring Mission (TRMM) rain datasets. Chen et al. (2006) used the same datasets to analyze the effects of vertical wind shear and storm motion on TC rainfall structures. Results show that TC rain asymmetry varies with TC intensity, storm motion, and shear strength. TC movement plays an important role in the asymmetric distribution of TC precipitation. In general, maximum rain rate is located in the down-motion quadrants relative to TC motion; however, it also varies with the speed of TC movement. Maximum convergence is mostly concentrated in down-motion quadrants for slow-moving TCs but more specifically in the down-motion right or left quadrant for fast-moving TCs over the Northern or Southern Hemisphere, respectively. However, early TRMM rain products were based on early versions of rain retrieval algorithms, which are not consistent among different passive microwave (PMW) sensors (Kummerow et al. 2001). The 3-yr TRMM-era observations are not sufficient to produce a robust climatology of TC precipitation for all storm intensity categories and not adequate to show the geographic variability of TC precipitation. Wingo and Cecil (2010) applied a 15-yr (1988–2002) TRMM, version 6 (v6), and the Remote Sensing System (RSS) v4 rain products at 0.25° grid resolution to study the effects of vertical wind shear on TC precipitation. However, these early-version rain products had an intensity limit of 25 mm h⁻¹, which is too low for TC rainfall. In addition, a spatial resolution (polar coordinate system) at 50-km radial bin × 45° azimuthal degree grid utilized by Wingo and Cecil (2010) was too coarse to display a clear TC precipitation variation near the eyewall and strong convection zones. There are many rain products from satellite-based rain retrieval algorithms and numerical weather prediction (NWP) model forecasts; however, the most accurate precipitation estimations based on satellite observations are from PMW sensors (Smith et al. 1998). Observations from satellite PMW sensors are best for displaying TC horizontal structures due to the capability of penetrating clouds from PMW frequencies (Hawkins et al. 2008; Yang et al. 2020). Thus, the PMW sensor-derived rainfall is the best dataset to study characteristics of TC precipitation. The quality of satellite-derived precipitation data has been improved significantly since the early version of TRMM rain products. The latest physical inversion-based PMW profiling rain retrieval algorithm (GPROF) for TRMM V8 products has evolved to generate the Global Precipitation Measurement (GPM) V05A rain products (Elsaesser and Kummerow 2015). This sophisticated rain retrieval algorithm has been applied to all PMW conical scan sensors so that precipitation from these sensors will be consistent and comparable. A maximum rain rate of 300 mm h⁻¹ is adapted in the updated GPROF algorithm so that GPM rain products have a proper range of rain rates to cover the TC precipitation magnitudes. In addition, the Automated Rotational Center Hurricane Eye Retrieval (ARCHER) scheme (Wimmers and Velden 2010, 2016) has been developed and applied to accurately locate center positions of TCs. Accurate locations of TC centers can lead to improved characterization of TC horizontal structures and its climatology based on a composition analysis. A more accurate climatology of TC precipitation will then lead to better forecasts of TC precipitation and evaluation of mesoscale numerical model TC predictions (Lonfat et al. 2007; Tuleya et al. 2007; Liu et al. 2008, 2010). Therefore, it is valuable to provide an improved climatology of TC precipitation and its geographic characteristics using recently available long-term and high-quality PMW sensor-based GPROF precipitation datasets.

2. Method and datasets

Accurate and consistent precipitation datasets from the recently updated GPROF rain retrieval algorithm for all PMW sensors during 1998–2012 are used to demonstrate the improved climatology of TC precipitation (NASA 2020). Accurate TC center positions are required to present a better climatology of TC precipitation when a composite method for a large dataset is used. The best-track datasets on TC intensity and position and the 200–850-hPa wind shear and movement from the Statistical Hurricane Intensity Prediction Scheme (SHIPS) are from NOAA and the Joint Typhoon Warning Center (http://rramb.cira.colostate.edu/research/tropical_cyclones/ships/index.asp; DeMaria et al. 2005; Knaff et al. 2005). ARCHER is applied to accurately locate the TC center position when PMW measurements are available and applicable (Wimmers and Velden 2016). The hourly-interpolated TC best track is taken as the initial input to ARCHER. The ARCHER fixing is applied if its return is reliable. Otherwise, the interpolated best track is selected. In general, 70% of cases show that the ARCHER fixed TC positions are more accurate than the best-track estimated positions. GPROF precipitations are first extracted for an area of 12° × 12° over TC center positions. These extracted TC precipitation datasets are then transferred into a polar coordinate system for better presentation of TC rain structure and composite analyses. This polar coordinate system has a radius of 500 km with 1-km resolution and azimuthal angles of 360 with a 0.5° resolution. This high-resolution scheme is selected to better display TC precipitation near the eyewall and a clear rainfall variation over convection zones and their surrounding areas. To study impacts of TC motion and the 200–850-hPa wind shear on TC precipitation distributions, three different composition coordinate systems are applied: storm center/north direction–relative, storm center/storm motion–relative, and storm center/vertical wind shear–relative coordinates. Storms only over oceans are utilized in this study. Precipitation in the polar coordinate system is rotated accordingly with the compass north direction, direction of TC movement, and vertical wind shear, respectively, before a composite process is conducted for all storms. Global TCs are traditionally classified into six TC basins defined by the Joint Typhoon Warning Center (JTWC) based on its center locations: the Atlantic (AL), central Pacific (CP), east Pacific (EP), Indian Ocean (IO), Southern Hemisphere...
(SH), and west Pacific (WP). Definitions of these basins and geographic locations can be found in the Automated Tropical Cyclone Forecasting System (ATCF) web page (ATCF 2007; see also Hawkins et al. 2001; Knaff et al. 2005; Yang and Cossuth 2016, their Fig. 1). Table 1 shows the distribution of observed TCs by satellite PMW sensors based on their intensities and locations during 1998–2012. There are more than 23,000 observed cases each for TD and TS during this period. There are also greater than 2000 samples for each TC category, except for category-5 TCs with only 437 cases. A total of 38.2% of TCs are located in WP while 24.9% and 21.6% of TCs are located in SH and AL, respectively; 11.8% of TCs are in EP, while CP and IO have only 1.7% and 1.8%. Thus, WP, SH, and AL are favored regions for TC activities. A total of 15,150 observed TCs are available for this study, which is more than 2 times the 6219 TC samples used in Wingo and Cecil (2010). In addition, the TD category was not included in their study. Thus, a regional variability of TC precipitation can be reasonably analyzed with this dataset. Overall, the dataset used in this study has sufficient observed TCs to provide a robust climatology of TC precipitation, although potential uncertainties exist for category-5 TCs over CP, EP, and IO due to relatively small samples.

3. Characteristics of global TC precipitation

a. Radial distribution of the azimuthal-averaged TC precipitation

Figure 1 presents an improved global climatology of TC precipitation in terms of radial distribution of the azimuthal-average rainfall according to all TC intensity categories. The prominent feature is how the amplitude of TC maximum rainfall increases with its intensity. A clear variation of rain intensity near the eyewall is evident. The maximum azimuthal-averaged rain intensity is 1.8, 3.1, 5.7, 7.5, 9.1, 11.4, and 15.3 mm h$^{-1}$ for TD, TS, and TCs of category (Cat) 1–5, respectively. The heavy-dashed line indicates the positions of maximum rainfall of TCs from weak to strong intensity. Maximum rain rate is located at 50-km radial distance for TD and TS, while it falls from 45 to 30 km as TC strength increases from Cat 1 to Cat 5. This result indicates a clear inward shift of maximum rainfall to the center position with an increase of TC intensity. Since the maximum rainfall location is associated with the TC eyewall, this shift demonstrates a contraction of the TC eyewall when TC intensity increases. Figure 1 shows that the decay of rain rate with radius is faster within 200 km than beyond 200 km. It is also evident that maximum rainfall jumps from TS/TD to Cat-1 TCs and from Cat-4 to Cat-5 TCs.
For comparison, the azimuthal-averaged precipitation was only available for TS, combined Cat-1/2 and combined Cat-3–5 TCs in Lonfat et al. (2004) because of the limited 3-yr observations. Because of the rain rate limit of 25 mm h\(^{-1}\) in the TRMM V5 GPROF dataset, Lonfat et al. (2004) displayed a small variation of rain intensity near the eyewall and an overall weak rainfall amplitude with a TS mean rain rate of 2.6 and 1.5 mm h\(^{-1}\) at a radius of 100 and 200 km, respectively. Cat-1/2 (Cat 3–5) TCs have a mean rain rate of 5.0 (6.7) mm h\(^{-1}\) at 100 km and 2.0 (2.1) mm h\(^{-1}\) at 200-km radius. However, this study indicates a magnitude of 2.8 mm h\(^{-1}\) at 100 km and 1.8 mm h\(^{-1}\) at 200-km radius for TS mean rain rate, while Cat 1–2 TCs have a range of mean rain rate of 5–6 mm h\(^{-1}\) at 100 km and 2.5–3.0 mm h\(^{-1}\) at 200-km radius. Cat-3–5 TCs have a range of rain intensity of 6.8–8.8 mm h\(^{-1}\) at 100-km radius and 3.0–3.5 mm h\(^{-1}\) at 200-km radius. In addition, the azimuthal-averaged radial patterns of TC precipitation in Wingo and Cecil (2010) were not able to resolve rain variation near the eyewall and variability with storm intensity due to a limited sample of dataset with a low spatial resolution. Therefore, the results presented here, in general, not only confirm the TC precipitation properties in Lonfat et al. (2004), but also reveal reliable, significantly large mean rainfall magnitudes and detailed characteristics of TC precipitation for all storm intensity categories due to a more accurate and consistent GPROF rainfall dataset from all PMW sensors and a much larger sample of observed TCs applied in this study.

b. Impact from TC movement

The climatology of TC precipitation horizontal distribution is best represented by a composite analysis of a large TC dataset. Climatology of precipitation distributions at each TC intensity category using the traditional composition method with the north direction is shown in Fig. 2. Concentric TC rainfall patterns up to a radius of 300 km are obvious for Cat-1–5 TCs when their center positions are accurately identifiable. Weak storm systems (TD and TS) present a less concentric rainfall pattern mainly due to a lack of less identifiable center positions within these storms. The concentric distribution of TC precipitation is expected because of the composite analysis with large sample size, although any individual TC has a unique asymmetric pattern of rainfall. Thus, this traditional
composition approach with the north direction is not appropriate to correctly show horizontal distribution of an individual TC precipitation.

It is therefore necessary to identify a better way to present the observed pattern of TC precipitation. The TC precipitation distribution pattern is well known to be associated with storm motion (Shapiro 1983; Lonfat et al. 2004; Chen et al. 2006). Figure 3 shows rainfall distributions with respect to direction of TC movement at each TC intensity category. Maximum precipitation is mainly located in the down-motion quadrants for TD, TS, and Cat-1–3 TCs, while a concentric rainfall pattern is obvious for Cat-4/5 TCs. It also indicates that a more intense storm is more resilient to impacts by its motion because its vorticity increases with increase of storm intensity. The magnitudes of precipitation are clearly corresponding to storm intensity categories. Compared with the TC precipitation pattern relative to storm motion shown in Lonfat et al. (2004) and Chen et al. (2006), this study displays a clear distribution and variation with storm intensity from TD to Cat-5 TCs. Results in general confirm the published features on motion-relative TC precipitation distributions and provide additional characteristics of TC precipitation distributions regarding to storm motion. An increase of precipitation in front of TCs from the enhanced convergence due to storm motion depends on storm intensities. Thus, the impact of storm motion on TC precipitation distribution is also related to storm intensity. The storm motion–enhanced convergence plays a major role in the distribution of precipitation for weak TCs, while its role is reduced for TCs with higher intensity. This observation indicates that other processes such as the thermodynamics and interactions with its environment have important impacts on TC precipitation distributions.

c. Impact from 200–850-hPa wind shear

The impacts of the 200–850-hPa wind shear on TC rainfall distributions are clearly shown in Fig. 4. The salient feature is a coherent location of maximum rain rate in the downshear left quadrant (DSLQ) for all storm intensity categories except TD, in which the maximum rainfall location is in front of the downshear direction. These properties demonstrate a
consistent spatial pattern of TC precipitation with respect to the direction of the 200–850-hPa wind shear. A close review of the distribution shows the position of maximum rainfall for weak storms (TD and Cat-1/2 TCs) is actually shifted to an azimuthal degree of 335°–360° relative to the vertical shear direction. Chen et al. (2006) analyzed wavenumber-1 TC precipitation asymmetry relative to the 200–850-hPa wind shear using the 1998–2000 TRMM v5 rain dataset and indicated

**Global composite rainfall on direction of vertical wind shear at each TC intensity category**

Fig. 4. As in Fig. 3, except relative to direction of the 200–850-hPa wind shear in a polar coordinate system. The light-white arrow indicates the direction of the vertical wind shear.

**Composite Precipitation Patterns for Global Major Hurricanes in 1998-2012**

Fig. 5. Comparison of the composite precipitation distributions for global major hurricanes between different composition methods relative to (left) the north direction, (center) the direction of the TC movement, and (right) the direction of the 200–850-hPa wind shear in a polar coordinate system. From left to right, the light-white arrows indicate northward, direction of the TC movement, and direction of the vertical wind shear, respectively.
maximum rainfall located in DSLQ. However, they did not
give a climatological distribution of TC precipitation and its
variability with storm intensity. Wingo and Cecil (2010)
presented a TC precipitation climatology using 15-yr low-
resolution rain dataset, but they were not able to display a
high-resolution distribution of TC precipitation and to show a
clear rainfall variation near TC center and eyewall. The rainfall
magnitudes in their study were lower than what is demon-
strated in this study. In addition, they were not able to present a
detailed variation of TC precipitation with storm intensity
because of the small sample sizes of observed TCs. However,
the sample sizes of observed TCs utilized in this study are more
than double the number in Wingo and Cecil (2010) due to in-
clusion of available Special Sensor Microwave Imager/Sounder
(SSMIS) and Advanced Microwave Scanning Radiometer for
Earth Observing System (AMSR-E) observations. The rainfall
properties established in this study not only confirm, in general,
previously published results on TC precipitation distribution
relative to the vertical wind shear direction, but also provide a
detailed pattern for each TC category and TS and a different
pattern for TD. Therefore, this study further demonstrates that
the vertical wind shear plays a crucial role in TC precipitation
distribution.

To better display the impacts with respect to the directions
of TC movement and vertical wind shear on TC precipitation
spatial distributions, Fig. 5 presents a comparison of TC pre-
cipitation spatial patterns for global major hurricanes with
respect to different composition methods. The circular pattern
of TC precipitation is obvious for the standard north direction
composition. Maximum rainfall is shifted to the down-motion
quadrants with respect to direction of TC movement, indicat-
ing an important role of TC movement in precipitation distri-
butions. This shift is due to contributions of Cat-3 TCs.
Maximum rainfall is located in the DSLQ regarding direction
of the 200–850-hPa wind shear. This shift of maximum rainfall
location demonstrates a more consistent pattern of TC pre-
cipitation with respect to vertical wind shear direction than to
the direction of TC movement (more detailed analysis is pro-
vided in sections 4b and 4c). This special feature indicates the
vertical wind shear plays a more important role than TC

FIG. 6. As in Fig. 1, but for all TC basins.
movement in TC precipitation distributions, which has a potential application for improving prediction of TC precipitation. Several rainfall forecasting models have been developed and applied for TC precipitation predictions. The Tropical Rainfall Potential (TRaP) model is designed with satellite rainfall estimates, persistence of TC intensity, and surface wind vectors (Kidder et al. 2005). A modified version called areal TRaP is developed to include a graphic view of TC rain horizontal distribution (Kidder et al. 2001). An Ensemble Tropical Rainfall Potential (eTRaP) scheme is developed by using estimates from multiple sensors observing the storm at different times to reduce uncertainties associated with satellite-derived rain rates and spatial rain structures (Ebert et al. 2011). A popular statistical model called Rainfall Climatology and Persistence Model (R-CLIPER) is based on storm size and intensity and azimuthal-averaged radial rainfall distribution (Tuleya et al. 2007). The Parametric Hurricane Rainfall Model (PHRaM) is developed to overcome the limitations of R-CLIPER by accounting for the asymmetric feature of TC precipitation due to geographic impacts and vertical shear conditions (Lonfat et al. 2007). A common requirement of these rainfall forecast models except eTRaP is the satellite-based TC rainfall climatology. Therefore, a more accurate azimuthal-averaged radial rainfall pattern and a detailed horizontal distribution of TC precipitation and its variations with storm intensity and motion as well as the vertical wind shear direction from this study should be able to improve the forecasting performance of TC rainfall of these models.

4. Geographic characteristics of TC precipitation

a. Radial distribution of the azimuthal-averaged TC precipitation

A review of the published literature indicates that global TC activities are concentrated in six TC basins (Gray 1998; Landsea 2006; Yang and Cossuth 2016). Different characteristics of TCs over different regions are identified by many studies (e.g., Fischer et al. 2018, 2019; Kaplan et al. 2015). However, there has been limited literature on geographic characteristics of TC precipitation because of a lack of high-quality precipitation datasets (Lonfat et al. 2004). The current GPROF precipitation dataset applied in this study is able to allow a solid analysis of geographic characteristics of TC precipitation because of robust samples of TCs over each TC basin.
Figure 6 presents radial patterns of the azimuthal-averaged TC precipitation for each intensity category over all basins. Similar radial patterns of the azimuthal-averaged TC precipitation are obvious among these basins. In general, sharp variation of rain intensity near the eyewall, contraction of the eyewall with an increase of TC intensity, and a decrease of rain intensity with distance to the TC center are the common characteristics of TC precipitation over these basins. These features are expected because the azimuthal average process diminishes the asymmetric feature of TC properties. However, note that there are uncertainties over IO, CP, and EP due to a relatively small size of TC samples there (see Table 1). Overlaps of the radial patterns for Cat 1/2 over IO and CP and the slow decrease of rain intensity with distance to TC center over CP are caused by the small sample size of available TCs. This uncertainty will be reduced significantly when more PMW measurements are processed in the near future.

b. Impact from TC movement

The geographic distributions of the composite TC precipitation relative to storm motion for each category are presented in Fig. 7. Maximum rainfall is located in the down-motion quadrants for low-intensity storms (TD, TS, and Cat-1 TCs), while Cat-2–4 TCs have maximum rain rate located in the down-motion right quadrant (DMRQ) over the AL basin (Fig. 7a). However, AL Cat-5 TCs still show a concentric rainfall pattern. The WP basin, in general, exhibits a consistent maximum rainfall in the down-motion quadrants for major hurricanes; although, the concentric feature of rainfall is still visible. Maximum rainfall in the down-motion left quadrant (DMLQ) is for TS and Cat-1/2 TCs while TD has a relatively large rainfall located in the down-motion quadrants (Fig. 7b). Over the SH basin, maximum rainfall is mostly located in the down-motion quadrants for all storm categories except Cat-5 TCs, which have a concentric pattern (Fig. 7c). EP and IO storms have similar patterns of rainfall distributions as WP storms, except TD with a relatively large rainfall in the DMLQ (figure omitted). CP storms have in general a maximum rainfall in the DMRQ except for Cat-5 TCs, which have a concentric rainfall pattern (figure not shown).

Results indicate a clear geographic variation of TC precipitation distribution relative to storm motion and intensity. The impact of storm motion on TC precipitation distribution is
more significant for weak storms than for storms with higher intensity. The impact is almost nonexistent for Cat-5 TCs, which have a persistent concentric rainfall pattern. As compared with results from Lonfat et al. (2004) and Wingo and Cecil (2010), detailed and fine distributions of TC precipitation are presented from this study. This accurate TC rainfall climatology and its variations with storm motion and intensity as well as geolocation are critical for the improvement of precipitation forecasts from existing TC rainfall models.

To clarify potential uncertainties associated with the relatively small sample size of Cat-3–5 TCs over the EP, CP, and IO basins, rainfall distributions of major hurricanes for all basins are shown in Fig. 8. The prominent feature is the various patterns of TC precipitation among these basins. Maximum rainfall is in DMRQ over AL, the down-motion quadrants over WP and SH, the left quadrants over IO and EP, and the right quadrants over CP. There also appear to be significant differences on the decrease of rain rate with distance from the storm center among these basins. Results not only confirm regional differences of the motion-relative patterns of TC precipitation in Lonfat et al. (2004) and Wingo and Cecil (2010), but also present the refined and detailed geographic properties of TC precipitation motion-relative distributions for all TC intensity categories, given the long-term and high-quality GPROF rainfall datasets utilized in this study.

This study demonstrates that geographic characteristics of TC precipitation distribution with respect to direction of TC movement are related to TC intensity and basin, indicating that TC movement is not the dominant forcing in determining horizontal distribution of TC precipitation. Other environmental conditions play more important roles for TC precipitation distributions, such as the vertical wind shear, which will be analyzed in following section.

c. Impact from 200–850-hPa wind shear

The importance of the 200–850-hPa wind shear on TC life cycle is well established (Willoughby et al. 1984; Marks et al. 1992; Black et al. 2002; Corbosiero and Molinari 2002; Fischer et al. 2019). Early studies also show regional differences on TC precipitation distributions impacted by vertical wind shear (Chen et al. 2006); however, detailed geographic features associated with each TC category were not found from these
published studies because abundant samples of observed TCs were not available. Figure 9 illustrates geographic characteristics of the TC precipitation distributions with regard to direction of the 200–850-hPa wind shear by displaying the composite precipitation patterns for every storm intensity category over the six TC basins. The prominent feature is that maximum rain rate is consistently located in DSLQ for all storm intensity categories and basins except TD, which has maximum rainfall located in the downshear quadrants, and the SH basin where maximum rainfall is consistently located in the downshear right quadrant (DSRQ). This clear difference of the TC maximum rain rate locations between the Northern Hemisphere and the Southern Hemisphere is correctly reflected by the opposite atmospheric circulations of TCs. A close look at precipitation distributions of Cat-5 TCs over IO and EP indicates their maximum rain rate is concentrated near the TC center (figure omitted). This observation is probably due to the relatively small samples of Cat-5 TCs over these two basins (see Table 1). The outstanding consistent TC rainfall pattern relative to direction of the 200–850-hPa wind shear and
storm intensity was not available in Lonfat et al. (2004) and Wingo and Cecil (2010). This feature can be adapted in PHRaM to improve TC rainfall forecasts.

To clarify uncertainties associated with small sample sizes for each of these intense TCs, a comparison of the composite precipitation patterns for major hurricanes over six basins is presented in Fig. 10. Rain rate distribution patterns show clearly a consistent pattern of the TC maximum rain rate located in DSLQ for all basins, except the SH basin where the TC maximum rain rate is located in DSRQ. It not only verifies results from Chen et al. (2006) and Wingo and Cecil (2010) on regional differences of TC rainfall distributions relative to the vertical wind shear, but also provides a more refined consistency of TC precipitation spatial patterns from the resulting high-quality and long-term GPROF precipitation dataset applied in this study. In addition, the improved smooth rain rate distributions for each basin indicate a reduced uncertainty because of the robust quantity of Cat-3–5 TCs. Even so, there is an indication of uncertainty in a small part of the 400–500-km radius in DSLQ of the CP basin where measurements of major hurricanes remain very limited relative to other basins. Therefore, the consistent TC spatial distribution and various magnitudes of TC precipitation over different basins are valuable to further improve TC rainfall predictions with these existing forecasting models.

Overall, results clearly demonstrate TC precipitation has a similar horizontal distribution pattern regarding the direction of the 200–850-hPa wind shear for all basins, that is, the maximum rainfall in DSLQ for all storms in the Northern Hemisphere and in DSRQ for all storms in the Southern Hemisphere, except TD whose maximum rain rate located in the downshear quadrants. It indicates that large-scale environmental forcing is the dominant factor in deciding horizontal distributions of TC precipitation. Although storm motion is important in TC precipitation distributions, it may play only a secondary role.

5. Discussion and conclusions

Analyses and results presented here not only verify the basic characteristics of TC precipitation in the published literature, but also provide an improved and accurate climatology of TC precipitation for every storm intensity due to utilization of
long-term, consistent, and high-quality GPROF precipitation from all PMW conical scan sensors as well as accurate TC center positions from ARCHER. TC eyewall contraction with TC intensity increase is well displayed by radius decrease of the azimuthal mean rain rate maximum from Cat-1–5 TCs. The long-term, consistent, and high-quality satellite-derived GPROF precipitation is crucial for presenting an accurate climatology of TC precipitation; however, an appropriate composition technique is also very important to provide accurate characteristics of TC precipitation. A composite method with the north direction is not appropriate for revealing the unique characteristics of a TC precipitation. Different spatial distributions of TC precipitation are prominent depending on whether a composition with direction of TC movement or direction of the 200–850-hPa wind shear is applied. At global scale, TC precipitation, in general, displays a maximum rain rate in the down-motion quadrants with regard to direction of TC movement, while presenting a well-organized and consistent spatial pattern with a maximum located in DSLQ with regard to direction of the 200–850-hPa wind shear.

TC precipitation has geographical variations with regard to direction of TC movement. This geographic feature is also related to TC intensities. Evidence revealed from this study indicates TC maximum rain rate for major hurricanes is located in DMRQ over AL, down-motion quadrants over WP and SH, left quadrants over EP and IO, and right quadrants over CP. For weak storms, maximum rain rate is located in down-motion quadrants over AL and SH, DMLQ over WP, EP, and IO, and DMRQ over CP. However, there is generally no geographical difference on horizontal distributions of TC precipitation with regard to direction of the 200–850-hPa wind shear. The maximum rain rate in DSLQ is consistent for every storm intensity category over all basins, except in the SH basin where maximum rainfall is in DSRQ. These characteristics not only verify previous published results, but also provide an improved and detailed distributions of TC precipitation for all storm intensity categories and TC basins. These results demonstrate that direction of the 200–850-hPa wind shear plays a dominant role in TC precipitation distribution, while the direction of TC movement has a secondary impact.

Improved TC precipitation climatology and refined spatial distribution pattern relative to direction of the 200–850-hPa wind shear could be utilized to advance predictions for TC precipitation. The existing TC precipitation forecasting models...
require an accurate satellite-based rainfall climatology to make reasonable rainfall forecasts. Early applications of these models applied the less accurate rainfall climatology from Lonfat et al. (2004) and Wingo and Cecil (2010). A better precipitation distribution and its variations with TC intensity and geolocations revealed in this study will provide an upgrade assumption of these models on precipitation climatology so that improved TC rainfall forecasts are expected if these new findings are implemented. This study provides robust observed TC rain rate distributions based on a long-term, consistent, and high-quality GPROF precipitation dataset from all satellite PMW sensor measurements. These characteristics and climatology of TC precipitation can be used to validate precipitation distributions from NWP model and mesoscale cloud model TC forecasts. Although the mechanism for the unique property of TC precipitation is not a focus of this study, a past study indicates a possible explanation for this TC rainfall pattern (Black et al. 2002). The potential mechanism for location of maximum rain rate is due to rapidly rotating tangential winds near the TC strong convection zone which creates a maximum vertical motion in DSLQ. The observed patterns of TC deep convection relative to the vertical wind shear direction, revealed from analysis of PMW sensor measurements at 89 GHz (Yang et al. 2020) are consistent with the precipitation distributions from this study.

Other satellite-based precipitation datasets could also be utilized to study properties of TC precipitation. The Japan Aerospace Exploration Agency (JAXA) Global Satellite Mapping of Precipitation (GSMaP) and the NASA Integrated Multisatellite Retrievals for GPM (IMERG) are the most popular precipitation products. GSMaP and IMERG provides a global hourly and 30-min rain rate with a 0.1° × 0.1° resolution, respectively (Kubota et al. 2007; Huffman et al. 2020). High temporal and spatial resolutions are both critically important to study the evolution of TC rain intensity and structures. Since GSMaP and IMERG rainfall are based on the combined rain retrievals from satellite PMW and IR measurements, accuracy of their products is not as high as the GPROF rain datasets. Whether the 30–60-min-averaged rainfall is suitable for TC applications is dependent upon the error analysis of these datasets. If the uncertainty is acceptable, GSMaP and IMERG, with high temporal resolution, will provide a great advance for TC applications. Unfortunately, this kind of analysis is not available. A direct comparison of
GSMaP and IMERG precipitation against the GPROF TC rain rates would provide reliable evidence of uncertainties of TC rain intensity and distribution for applying GSMaP and IMERG rain products. A preliminary study indicates that GSMaP rainfall can present basic characteristics of TC precipitation with obvious uncertainties. Further in-depth investigation is required before GSMaP and IMERG are applied for TC-related studies.

Detailed analysis of the impacts of both amplitudes of the 200–850-hPa wind shear and speed of TC movement on TC precipitation is beyond scope of this study, although Chen et al. (2006) showed some evidence of their impacts. Their combined impacts associated with TC intensity could lead to a detailed analysis of a net effect on TC precipitation amplitudes and distributions for various storm intensities and the ambient conditions. A wavelet analysis could also be useful in providing additional information about which dominant mode is in control of the TC precipitation patterns. In addition, uncertainty still exists over the EP, IO, and CP for TCs with higher intensity because of the limited TCs

Fig. 10. As in Fig. 8, but for direction of the 850–200-hPa vertical wind shear.
observed by PMW sensors in this study. Additional PMW sensor measurements from recent years will increase sampling of major hurricanes over these areas, especially over CP, which will lead to a decrease of uncertainties on TC precipitation distributions. These topics will be the focus of future studies.

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