Analyzing Relationships between Tropical Cyclone Intensity and Rain Rate over the Ocean Using Numerical Simulations

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ABSTRACT: In this study, the relationship between tropical cyclone (TC) intensity and rain rate over the ocean is investigated using a full-physics numerical model (WRF) and a physics-based TC rainfall model (TCR). TC intensity is found to be nearly linearly correlated with the average rain rate in the inner core [−0.97 (mm h⁻¹ m⁻²)/(m s⁻¹)], while the correlation is weak at outer radii. This difference is induced because TC intensity is significantly correlated with both the vertical velocity and specific humidity in the inner core but is not significantly correlated with the vertical velocity in the outer radii. Further investigation shows that the intensity–rain-rate relationship at the outer radii is influenced by the TC evolution stage. The rain rate for the outer radii is positively correlated with TC intensity for nondecaying TCs, while this correlation is reduced for decaying TCs due to systematic downdrafts in the outer radii. In the context of climate change, the sensitivity of the TC rain rate to sea surface temperature (SST) is found to be +9% per 1 K increase of SST, roughly the product of the sensitivity of TC intensity to SST (+3%) and the Clausius-Clapeyron scaling (+7%). Coupled with synthetic storms, evolution of the TC rain rate over the twenty-first century under the SSP5-8.5 scenario is projected by the TCR (calibrated with the WRF simulations). The annual increase rates of averaged TC rain rate are 0.17% and 0.20% for the inner core and outer radii, respectively, larger than the annual increase rate of TC intensity (0.046%) but comparable to that of cube of intensity (0.18%).

KEYWORDS: Atmosphere; Rainfall; Tropical cyclones; Climate change; Model evaluation/performance

1. Introduction

Rainfall from tropical cyclones (TCs) is hazardous and the future change of TC rain rates has been a focus of recent studies (e.g., Guzman and Jiang 2021; Tu et al. 2021). Climate models project an increase in the TC inner-core rain rates in the future (Knutson and Tuleya 2008; Knutson et al. 2010; Liu et al. 2019), which may lead to more destructive hazards associated with extreme TC rainfall events (Scoccimarro et al. 2014; Emanuel 2017). These studies point to a more challenging future for coastal areas, such that more TCs with heavy rainfall like Hurricane Harvey in 2017, Hurricane Florence in 2018, and Hurricane Ida in 2021 may occur under climate change.

The warming of the atmosphere can increase the saturated specific humidity by 7% per 1 K increase of the air temperature (i.e., Clausius-Clapeyron scaling). However, Knutson et al. (2013) showed that the increase of TC-related rain rate cannot be approximated by the Clausius-Clapeyron scaling. Liu et al. (2019) found that the rain rate within 100 km of the TC center can increase by 15%–30% per degree of air temperature rising in simulations. They associated this super-Clausius-Clapeyron scaling with the increase of TC intensity (maximum sustained wind near surface) in a future warming climate, which is an extra factor to consider relative to the rainfall–temperature scaling in other weather systems. An increase in TC intensity has been projected by most climate models (Knutson et al. 2020). As observational studies show that intense TCs tend to produce high rain rates, especially at the TC center (Lau and Zhou 2012), the future TC rain rates are very likely to increase due to the projected TC intensity increase.

Although extensive studies have investigated the increases in TC intensity and rain rate in future climates (e.g., Bengtsson et al. 2007; Kim et al. 2014; Scoccimarro et al. 2014; Villarini et al. 2014; Patricola and Wehner 2018), detailed analysis is lacking on the relationship between TC intensity and rain-rate changes. Although Liu et al. (2019) linked the increase of future TC rainfall with TC intensity change, the scaling between TC intensity and rain rate has not been established. The variability of the scaling in different TC radii and the causation of the radial variability also need to be investigated to better understand future TC rainfall changes. Answering these questions, which is the main objective of this study, is of crucial importance as it may provide a new angle to project future TC rain-rate changes via the increase of intensity in a warming climate.

To explore the linkage between TC intensity change and TC rain-rate change, we employ the Weather Research and Forecasting (WRF) Model to simulate idealized TCs with various intensities by varying sea surface temperature (SST) forcings. We also use a simplified, physics-based TC rainfall model (TCR; Emanuel 2017) to evaluate the rain-rate–intensity relationship and compare it with the WRF simulations. The TCR model simulates TC rainfall based on TC rainfall mechanisms including the frictional convergence, vortex stretching, topographic forcing, and baroclinic effect. This simplified TC rainfall model is computationally efficient and...
has been used for climate projection and hazard assessment (Emanuel 2017; Feldmann et al. 2019; Gori et al. 2022; Xi and Lin 2022). We use both WRF and TCR models to investigate TC rain-rate–intensity scaling by performing regression analysis for the TC intensity and rainfall in storm inner and outer regions. As SST greatly influences TC intensity, we also examine the scaling between TC rain-rate and SST changes using WRF simulations. The TCR model is further coupled with the synthetic storms downscaled from six climate models from phase 6 of the Coupled Model Intercomparison Project (CMIP6) to analyze how TC rainfall will change in response to TC intensity change in the future climate (the SSP5-8.5 scenario).

The goals of this research include 1) establishing quantitative scaling between TC rain rate and intensity, 2) understanding the different mechanisms between TC rain rate and intensity in the inner and outer regions of TCs, and 3) understanding how TC rain rate will change with SST and TC intensity in a changing climate. The paper is organized as follows. Section 2 introduces the WRF model setup and the TCR model used in this study. In section 3, we will define the radial inner and outer regimes in a TC and discuss how the different rainfall mechanisms in the two regimes influence the scaling relationship between the local rain rate and TC intensity. We explore the scaling relationship between TC rain-rate and SST changes. We also leverage synthetic storms datasets and the TCR model (calibrated with the WRF simulations) to investigate the rain-rate change in response to TC intensity change under climate change over the twenty-first century. Section 4 summarizes the main findings.

2. Methods
   a. WRF setup and experiment design

The WRF model (version 3.9.1.1; Skamarock et al. 2008) is used to simulate idealized TCs over the ocean with a double nested domain, 36 vertical layers, and a grid spacing of 3 and 15 km in the inner (2400 × 2400 km²) and outer (9000 × 9000 km²) domains, respectively. The inner domain is vortex following and the outer domain is static. The parameterization schemes are summarized as follows. The Rapid Radiative Transfer Model (RRTM) scheme (Mlawer et al. 1997) and Dudhia (1989) scheme are used for the longwave and shortwave radiation. Boundary layer processes are parameterized with the Yonsei University (YSU) scheme (Hong et al. 2006). No cumulus convection schemes are used in either domain since 3-km resolution is fine enough to resolve convections in the inner domain. The WSM single-moment six-class scheme (SM-6) (Hong and Lim 2006) is used for microphysics parameterization. No background wind is applied in the environment. The WRF setup in this study follows Wang and Toumi (2018) because their setup was shown to produce realistic TCs, and we will later make connections between TC rainfall and SST changes using the scaling relationship between TC intensity and SST changes found in Wang and Toumi (2018). Also, the equilibrium environment that the idealized TCs embedded in are obtained using the parameterization settings in Wang and Toumi (2018) (detailed later) and the settings of simulations of TCs need to be consistent.

To generate TCs with different maximum intensities, we perform five simulations with different SSTs (26°C, 28°C, 30°C, 32°C, and 34°C). To let the idealized TCs develop in realistic environments under different SST forcings, we perform the radiative-convective equilibrium (RCE) adjustment under the different SST forcings to obtain the equilibrium sounding profiles of thermodynamic parameters before the TC simulations are performed. The RCE adjustment is performed following Wang and Toumi (2018). The adjustment will influence various parameters that may be important for TC rainfall such as ambient air temperature and humidity. After the environmental profile is adjusted, the TC simulations are performed. In each simulation, a weak vortex is placed in the southeast of the outer domain because beta drift would drive the vortex to move northwestward in the Northern Hemisphere. Figure 1a shows the initial location of the weak vortex. Then each simulation runs for 10 model days to let the vortex develop into a steady state, and we extract the time series of intensity, radius of maximum wind (RMW), and rain rate of the simulated TCs. The evolution of TC intensity of these idealized TCs is shown in Fig. 1b.
b. TCR setup and simulations

The detailed formulation of the physics-based TCR can be found in Lu et al. (2018), and here we only review the model briefly. In TCR the rain rate $P_{\text{rate}}$ is simulated as

$$P_{\text{rate}} = \varepsilon_p \rho_{\text{air}} q w \quad \text{(when } w > 0), \tag{1}$$

where $\varepsilon_p$ is precipitation efficiency and $\rho_{\text{air}}$ and $\rho_{\text{liquid}}$ are the density of water vapor and liquid water, respectively. The ratio between $\rho_{\text{air}}$ and $\rho_{\text{liquid}}$ is set to be 0.0012 following Lu et al. (2018). Also, $q$ is the specific humidity (generally at 900 hPa), and $w$ is the vertical velocity. In this study we refer to the term $qw$ as vertical vapor transport. As SST has a profound influence on TC intensity and environmental humidity, the vertical vapor transport is also influenced by SST. When we compare WRF and TCR models, we evaluate both $q$ and $w$ at the top of the boundary layer, where the height of TC boundary layer is estimated from the YSU boundary layer parameterization scheme in WRF. TCR estimates the vertical velocity $w$ by the simple summation of vertical velocity components generated by the following mechanisms: boundary layer friction, vortex stretching, topographical effect, baroclinic effect, and radiative cooling.

The TCR-simulated rainfall is compared with WRF simulations. The specific humidity and smoothed azimuthally averaged wind profile from WRF simulations are used to drive the TCR simulation for consistency [following Lu et al. (2018)]. We perform sensitivity analysis of TCR by setting the drag coefficient as 0.001, 0.0012, and 0.0014. This range of drag coefficients was used in previous TC rainfall simulations (Lu et al. 2018; Feldmann et al. 2019). Other parameters are consistent with those in Xi et al. (2020).

c. Synthetic storm dataset

To understand the TC rain-rate increase under climate change, we perform physics-based TC rainfall downscaling using synthetic storms and TCR. We use the synthetic TC dataset downscaled from six CMIP6 climate models (CanESM5, EC-Earth3, IP-SL-CM6A-LR, MIROC6, MPI-ESM1-2-HR, and MRI) under control and Shared Socioeconomic Pathway 5-8.5 scenarios (SSP5-8.5) by a statistical-deterministic TC model (Emanuel et al. 2008; Emanuel 2021). The synthetic storm model simulates TC track using statistics of environmental winds and estimates TC intensity along the track using a coupled atmospheric and ocean model (Emanuel et al. 2008). The downscaling is performed for years 1980–2010 by Emanuel (2021). The synthetic datasets include 150 storms simulated per year in the control period (1980–2014) and 200 storms per year in the projection period (2015–2010). As we focus on the average TC rain rate, the large number of storms in the dataset help us obtain robust results. The different numbers of synthetic storms in control and future periods reflect the increase in TC frequency in the future climate projected by this synthetic storm model (Emanuel 2021).

d. Analysis methods

We examine the relationships between TC rain rate and TC intensity and discuss how this relationship depends on the radial location in a TC. We interpolate the rainfall profile into each rescaled radius (i.e., the distance to the TC center divided by RMW). We use the rescaled radius to partly reduce the influence of TC size variation so that we can better link the rain rate with different rainfall mechanisms along the radii. We first examine the rainfall and thermodynamic parameters at each individual rescaled radius, and then group the radial areas into inner-core and outer-radii regions to analyze the dependency of TC rain rate on TC intensity in each regime. The inner-core and outer-radii regions are separated at 2.5 RMW according to the different mechanisms of TC rainfall in these regions (detailed later).
3. Results

a. Radial variation of the relationship between TC rain rate and intensity

We begin with evaluating how the TC rainfall at different radii depends on TC intensity. Figure 2 shows the regression analysis between TC intensity and rain rate in both WRF and TCR. The rainfall in the vicinity of the eyewall is more sensitive to TC intensity than at outer radii, and the coefficient of determination $R^2$ is found to be the highest around 1–2 RMW (Fig. 2a). The TC intensity and rain rate are positively correlated (positive slopes) from 0 to 7 RMW (Fig. 2b). TCR behaves similarly to WRF in terms of reproducing the relationship ($R^2$ and slope) between TC rain rate and intensity, with slightly higher correlation between rain rate and intensity relative to WRF at outer radii (Fig. 2a). The correlation between rain rates in TCR and WRF is high, and the regression slope is close to 1 (except within 0.5 RMW and outside 5.5 RMW), which means that TCR has satisfactory capacities of reproducing the rainfall features in WRF.

b. Dependency between TC rain rate and intensity in the simulations

In this section, we define two regions within a TC, the inner-core region and the outer-radii region, and analyze the dependence of the averaged rain rate on TC intensity in each region. Before the analysis, we need to select a reasonable re-scaled radius to separate the inner core and outer radii. The 2.5 RMW is chosen in the following analysis as a boundary to divide the inner and outer regions considering the different patterns of the simulated radar reflectivity (dBZ) and vertical transport of water vapor ($qw$) as shown in Fig. 3. The
reflectivity within 3 RMW is much higher than that beyond this threshold, showing that the inner-core rainfall is more related to convective processes. Significant positive low-level vertical vapor transport is constrained within 2 RMW, indicating that the main convective transport of vapor is confined in the inner core. Thus, we select 2.5 Rm as the boundary to separate the inner core and outer region. Sensitivity analysis using threshold of 2 or 3 RMW rendered similar results.

Figure 4 shows the relationship between simulated TC intensity and rain rate by WRF and TCR in the inner core (Fig. 4a) and outer radii (Fig. 4b). The TC intensity and the rain rate in the inner core are found to roughly follow a quadratic relationship though a linear approximation is also reasonable from a statistical perspective [regression slope $0.97 \text{ mm h}^{-1} \text{ m}^{-2}/\text{m s}^{-1}$; Fig. 4a]. TCR shows a similar rain-rate–intensity relationship as WRF in the inner core, and its regression slope is positively related to the drag coefficient (linear regression slope ranges from 0.86 to 1.15). However, TCR behaves differently from WRF in the outer radii. In the WRF simulations we see a clear separation of TC rain-rate response to intensity. In one branch (within the solid box in Fig. 4b), fitted by the red dashed line in Fig. 4b, the rain rate is linearly related to TC intensity (with a slope of 0.17). In the other branch (within the dash-outlined box in Fig. 4b), fitted by the blue dashed line, the rain rate stays almost constant even though the TC intensity varies. TCR simulations also show similar separation of TC rain rate response to intensity, but not as clearly as in the WRF simulations.

We will answer why in the outer radii there are separations of the relationship between TC rain rate and TC intensity in section 3c, while in this section we aim to understand what controls the dependency of TC rain rate on TC intensity. Figure 5 shows that in both inner core and outer radii, the TC rain rate is highly dependent on the vertical water vapor transport ($q_w$) at the top of the boundary layer. This dependence is also the backbone of the TCR model [Lu et al. 2018 and Eq. (1) of the present paper]. The vertical vapor transport across the top of the boundary layer is highly correlated with TC intensity and rain rate, but not as clearly as in the WRF simulations.

To understand which individual variable—the vertical velocity or the specific humidity at the top of the boundary layer (output directly from WRF model)—determines the cross–boundary layer vertical vapor transport, we examine
the relationship between the water vapor transport with these two variables (Fig. 6). In the inner-core region, both vertical velocity and specific humidity are highly correlated with the cross-boundary layer vapor transport. In the outer radii the specific humidity is, however, not correlated with the cross-boundary layer vapor transport ($R^2 = 0.05$; Fig. 6d); that is, the vertical velocity at outer radii solely controls the water vapor transport within the outer region.

The relationship between TC intensity, vertical velocity, and specific humidity is shown in Fig. 7. The vertical velocity and specific humidity at the top of the boundary layer are averaged in the inner-core and outer-radii regions. In both the inner core and the outer radii, specific humidity is highly correlated with TC intensity, but the vertical velocity is only correlated with intensity in the inner core. [The relationships between the local convective available potential energy (CAPE; averaged within the inner core or outer radii, related to convection intensity) and vertical velocity in the inner and outer regions are similar to the relationships between TC intensity and vertical velocity; not shown.] In the inner core, the intensity is linearly correlated with both specific humidity and vertical velocity, which can explain the superlinearity of their product ($qw$) with intensity as shown in Fig. 4a. Intuitively, higher intensity is associated with warmer SSTs (specified as input in the WRF simulation), stronger secondary circulation, and, thus, enhanced averaged vertical water vapor transport at the top of the boundary layer. Both the vertical velocity and specific humidity in the inner-core region determine the cross-boundary layer vapor transport, and thus TC intensity and the rain rate in the inner core are simply correlated. In the outer radii, TC intensity correlates with specific humidity most likely because intense TCs are associated with higher SSTs, under which condition the near-surface environmental humidity is higher. TC intensity is not simply correlated with vertical velocity, which determines the cross-boundary layer vapor transport in the outer radii, and that explains why TC intensity and rainfall show limited correlations in this region.

c. Outer-radii rain rate and TC intensity

In section 3b, we discussed the statistical dependency between TC intensity and rain rate in the inner core and outer radii. One remaining question is why the dependency of TC rain rate at outer radii on TC intensity separates into two branches. Here we separate TC evolution stages by defining the intensifying, decaying, or neutral state by performing the linear regression between the simulation time and the
averaged TC intensity within each 24-h period. If the linear relationship is not statistically significant, we refer to this 24-h period as a neutral state. If the linear relationship is statistically significant, we determine whether the storm is intensifying or decaying by the sign of the regression slope. We find that the dependency of the TC rain rate on TC intensity is highly influenced by the intensity evolution of TCs. Figure 8a shows how the outer-radii rain rate of a TC is related to TC intensity when a TC intensifies, decays, or is in a neutral state.

When a TC decays, the rain rate at outer radii stays stable (i.e., independent of TC intensity). When a TC holds a stable intensity or intensifies, the TC rain rate is positively correlated with TC intensity. Figure 8b shows the evolution of averaged intensity in the three scenarios in the simulations.

Because TCR cannot capture the separation well (Fig. 4b) but we need to use TCR for climate change analysis (section 3e), the TCR must be modified to better simulate outer-radii rainfall as in WRF. TCR predicts the rainfall by calculating the vertical...
velocity in TCs. The vertical velocity is predicted as a sum of the vertical velocities caused by frictional convergence, vortex stretching, topographic forcing, baroclinic effect, and radiative cooling. In our study, topographic forcing and baroclinic effect do not exist due to our idealized settings in the WRF simulation. From Lu et al. (2018), the summation of the frictional and vortex stretching terms is physically reasonable, as they are derived together from the angular momentum equation. However, the addition of the radiative cooling term is ad hoc. Also, the assumption of the vertical velocity caused by radiative cooling being constant is not supported by previous research as the radiative cooling is affected by the clear-sky outward radiation and the atmospheric stability (Chavas and Emanuel 2014). Thus, we modify the radiative cooling term in TCR to statistically match with the WRF simulations, for intensifying, neutral, and decaying TCs, separately. The obtained optimal values of vertical velocity resulting from radiative cooling in neutral, decaying, and intensifying TCs are \(-0.013\), \(-0.014\), and \(-0.005\) m s\(^{-1}\), respectively. Figure 8c shows that the modified TCR with the optimal radiative cooling velocity can well capture the relationship between TC intensity and the outer-radii rain rate in the two separate branches. In section 3d, we will use the modified TCR to examine TC rainfall changes in future climates.

To understand why the dependency of outer-radii rain rate on TC intensity is influenced by the evolution stage of TC intensity, we analyze the vertical cross section of radial averaged reflectivity in WRF simulations (Fig. 9). In comparison with the intensifying and neutral storms, the high-reflectivity region is narrower in the decaying storms, even though when TC decays, the radius of maximum wind expands. The high-reflectivity (e.g., >15 dBZ) region is within 2.5 RMW for the decaying storms, but the high-reflectivity region expands to 4 RMW for the neutral and intensifying storms. This result implies that in the decaying storms, the convection beyond 2.5 Rm is suppressed. The vertical velocity across the top of the boundary layer is mostly negative in outer radii for decaying storms while the velocity is positive for neutral and intensifying storms (not shown here), indicating that there are systematic downdrafts exist in the outer radii of decaying storms, and those downdrafts inhibit the convection in the TC outer radii.

The above analysis shows that the rain rate in the outer radii is highly influenced by the intensity evolution of TC intensity, and the convection in outer radii in decaying storms is suppressed so that outer-radii rainfall for decaying storms is very weak. Future studies could use finer grid numerical simulations and case studies to understand the detailed mechanisms for convection inhibition in outer radii in decaying storms.

d. SST and the rain rate

In previous sections, we analyzed the scaling between the TC rain rate and TC intensity. As shown in Wang and Toumi (2018), the sensitivity of TC intensity to SST is about 3%-4% per K; it is of interest to show the sensitivity of the TC rain rate to SST. Figure 10 shows the hourly accumulated rainfall from the storm center to the radius of 600 km, which is used in previous studies to represent TC total rainfall (Xi et al. 2020). The rain rate increases as the SST increases, and the sensitivity is around 9% per K. The sensitivity is obtained by calculating the averaged relative increase rate of TC rainfall per degree increase of SST. The Clausius-Clapeyron scaling

FIG. 9. WRF-simulated averaged radial cross section of reflectivity (dBZ) for (a) decaying storms, (b) intensifying storms, and (c) neutral storms.

FIG. 10. Time evolution of storm total rain rate from 0 to 600 km from the TC center in WRF simulations.
shows the saturated water vapor content should increase by 7% per K of temperature increase (Held and Soden 2006), but the increase in the rain rate in our analysis is higher than this scaling, because the increase of TC intensity makes an extra contribution to the increase of TC rain rate. The product of the sensitivity of TC intensity to SST (3%–4%) and the Clausius-Clapeyron (7%) renders a 10% increase of rainfall (103% × 107% = 110%), comparable to our scaling of 9%, and the small difference could result from the fact that TC intensity and outer-radii rainfall are not simply correlated (Fig. 8a). We consider the product of the sensitivity of TC intensity to SST and the Clausius-Clapeyron scaling because Eq. (1) shows TC rainfall can be approximated by the product of storm vertical velocity (related to storm intensity) and specific humidity. Similar to Liu et al. (2019), we use Clausius-Clapeyron scaling to link SST to low-level saturation specific humidity, because the change of SST is similar to the change of air temperature at near-surface levels, which is also shown in our RCE simulations. Our analysis implies that the increase of water vapor content in the atmosphere and TC intensity influence the TC rain rate increase in a multiplicative manner.

c. Climate projection of TC rain rate

From section 3b, we found that TCR can reproduce the correct sensitivity of TC rain rate to TC intensity in the inner core. We also modified TCR so that it can reproduce the correct sensitivity of TC rain rate to the TC intensity in outer radii (section 3c). We next couple the TCR model with the synthetic storms downscaled from six global climate models to understand the average rain rate change in future climates, in comparison with the change in TC intensity. Figure 11 shows the global evolution of the estimated TC rainfall from 1980 to 2100 while the TC is over the ocean. We only look at TC rainfall over the ocean because the TCR is validated against WRF using idealized TCs that are simulated over the oceans. We found that the averaged TC rainfall in the inner core and outer radii will increase significantly in the future under the SSP5-8.5 scenario. The annual increase in inner-core rain rate is 0.0112 mm yr<sup>−1</sup>, and the increase in outer-radii rain rate is 0.0057 mm yr<sup>−1</sup>. The annual increase rates are 0.17% and 0.20% for the inner-core and outer-radii rain rates, respectively. Although the absolute value of the increase in inner-core rain rate is higher than that in the outer-radii region, the relative increase of outer-radii rain rate is larger due to its lower value in the current climate.

It is of interest to evaluate how the averaged TC rainfall change as compared with TC intensity change. The comparison may indicate if the increase in TC rainfall hazard is more significant than the increase in TC wind hazard. Figure 12 shows the global evolution of averaged intensity, kinetic energy (square of intensity), and cube of intensity. The average cube of TC intensity can be viewed as the power dissipation index (Emanuel 2005) divided by the total storm duration in a year. The annual increase rates of the averaged TC intensity, kinetic energy, and cube of intensity are 0.046%, 0.10%, and 0.18%, respectively. It is found that the increase rate of rainfall is higher than the increase rate of TC intensity and kinetic energy but comparable to the increase rate of the cube of intensity. Emanuel (2005) argued that the power dissipation index is related to the wind damage produced by the TCs. Thus, the change in cube of intensity may also be used to approximate the change of TC rainfall damage under climate change. One possible explanation of why TC rain-rate change is closest to the change of the cube of TC intensity could be as follows. In TCR, the rain rate is dominated by the frictional convection (Lu et al. 2018), and the highest order of wind speed in calculating the frictional convection is 3 [see Eqs. (6) and (8) in Lu et al. 2018]. Thus, the change in TC rain rate is on a similar scale as the change in cube of TC intensity.

4. Summary and conclusions

In this study, we investigated the TC rain–intensity relationship using both full physics and simplified numerical models.
We found that the rain rate in the TC inner core is positively correlated with TC intensity, with 1 m s\(^{-1}\) increase of TC intensity leading to \(\sim 0.97\) mm h\(^{-1}\) increase of the TC rain rate in WRF simulations and approximately 0.86–1.15 mm h\(^{-1}\) increase of the TC rain rate in TCR simulations. Considering the sensitivity of TC intensity to SST and the dependency of rain rate on TC intensity, we investigated the sensitivity of TC rainfall to SST. We found that TC total rainfall will increase by around 9% per K increase of SST. Such an increase can be understood by the product of the sensitivity of TC intensity to SST and Clausius-Clapeyron scaling. The positive correlation between the TC inner-core rain rate and intensity is a result of both convection and water vapor content in the inner-core region being positively correlated with TC intensity. The outer-radii rain rate is not simply correlated with TC intensity. In outer radii, TC intensity is linearly correlated with the water vapor content, but the vertical velocity is not significantly correlated with TC intensity. For the TCs that are not decaying, the vertical velocity crossing the TC boundary layer increases linearly with TC intensity; for the decaying TCs, the outer-radii vertical velocity keeps almost constant (<0) while TC intensity varies, which causes the dependency of TC rain rate on TC intensity to differ between decaying TCs and other TCs.

A simplified physics-based TC rainfall model, TCR, is compared with WRF to evaluate its performance in reproducing the relationship between TC intensity and rain rate. TCR compares well to WRF in the TC inner core. In the outer radii, the model is not able to capture the different relationships between TC intensity and rain rate under different evolution stages of TC intensity. A linear regression that reweighted the radiative cooling term improved the TCR performance.

Coupling the modified TCR with a synthetic storm model, we evaluated the future evolution of TC rainfall to the end of this century. We found that under the SSP5-8.5 scenario, the annual increase rates of TC-averaged inner-core and outer-radii rainfall are 0.17% and 0.20%, respectively. The annual increase rate of TC rainfall is higher than that of TC intensity (0.046%) but is on a similar scale to that of the cube of TC intensity (0.18%).

This research provides an idealized-simulation-based analysis of the dependency of TC rain rate on TC intensity, which is then applied to TC rain-rate projections in future climates using a deterministic-statistical TC model. Future research could test the scaling relationships found in this study with fine-resolution climate models that are run through this century. Furthermore, the detailed mechanisms of TC rain rate at outer radii that cause the rain rate to be differently related to TC intensity under different evolutionary stages of TCs are worth further exploration. Better understanding of TC outer-radii rainfall may improve both climate projections and real time forecasting of TC rainfall.

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Data availability statement. Historical observations of tropical cyclones can be found at https://www.ncdc.noaa.gov/iitracs/. Satellite observation of tropical cyclone rainfall can be found at https://gpm.nasa.gov/missions/trmm. Input data for the WRF simulation can be found at https://www2.mmm.ucar.edu/wrf/users/download/free_data.html. The original synthetic tropical cyclone datasets used in this study are freely available from Kerry Emanuel for research purposes. For the details and availability of the synthetic datasets, please refer to Emanuel (2021; https://doi.org/10.1175/JCLI-D-20-0367.1).

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