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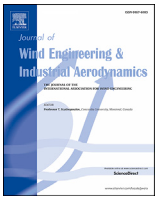

# An analytical framework for rapid estimate of rain rate during tropical cyclones

Reda Snaiki, Teng Wu *

*Department of Civil, Structural and Environmental Engineering, University at Buffalo, State University of New York, Buffalo, NY 14126, USA*

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ABSTRACT

An analytical framework for rapid estimate of rain rate during a translating tropical cyclone was proposed in this study. The efficient analysis framework for rain field is based on the observation that rain-induced momentum flux at Earth's surface cannot be ignored. The total surface stress results mainly from momentum flux contributions of wind and rain. A height-resolving wind field was utilized during the model construction leading to a linear, analytical solution of the surface rain rate. The obtained rain rate model explicitly depends on parameters for a typical tropical cyclone wind field simulation, namely storm location, approach angle, translation speed, radius of maximum wind, pressure profile, surface drag coefficient, and turbulent diffusivity. Hence, it could be readily implemented into state-of-the-art tropical cyclone risk assessment using the Monte Carlo technique. The rainbands in the proposed methodology were simulated using a local perturbation scheme. Sensitivity analysis of the rainfall field to the abovementioned parameters was comprehensively conducted. The results generated by the present analytical framework for rapid estimate of rain rate during tropical cyclones are consistent with field measurements.

## 1. Introduction

Tropical cyclones are responsible for the substantial part of natural hazard-induced economic and life losses through high winds, torrential rain and wind-driven storm surge. Among these, the rainfall-induced inland flooding contributes to a significant portion of the tropical cyclone related damages (e.g., Landsea, 2000; Rappaport, 2000). Therefore, the rain field simulation inside the tropical cyclone has attracted interest of a number of researchers for a better rainfall hazard assessment. While there have been considerable advances in improving the simulation accuracy of tropical cyclone rain field based on high-fidelity numerical weather prediction models, they are not practical for risk assessment due to their high computational demands. Usually, the rainfall distribution can be efficiently characterized based on probabilistic, parametric or physically-based schemes.

The probabilistic models give good insights on the exceedance rate of specific rainfall intensities, and are often used to predict the extreme rain rates. The development of this type of models usually suffer from a lack of a large number of historical data that are needed to fit the selected distributions. In addition, they are generally unable to represent the most important physics governing the rain field inside the tropical cyclone (e.g., sea surface temperature, moisture distribution, vertical wind shear, hurricane intensity and translational velocity). Actually, no physical justification has been provided for the use of the popular distributions such as lognormal, mixed-exponential and Gamma curves to fit the data (e.g., Woolhiser and Roldan, 1982; Groisman et al., 1999; Wilson and Toumi, 2005).

The construction of the parametric models also requires a huge amount of rain field measurements. Recently, the Tropical Rainfall Measuring Mission (TRMM) (Huffman et al., 2010), a joint satellite mission of the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA), has released a significant amount of tropical cyclone rainfall data. The goal of TRMM is to provide good estimates of global precipitation using satellite observations. TRMM contains several instruments, namely the TRMM Microwave Imager (TMI), the Precipitation Radar (PR), the Visible Infrared Scanner (VIRS), the Lightning Imaging Sensor (LIS), and the Clouds and Earth's Radiant Energy System (CERES). Details of the TRMM instruments are given in Kummerow et al. (1998). Several empirical models have been developed based on the TRMM database. For example, Lonfat et al. (2004) acquired the spatial distribution of the rain field over the ocean using the TMI data from 1998 to 2000. The rain rates were found to be heavily dependent on the sustained surface wind speed. The rain rate achieved the maximum value near the radius of maximum

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* Corresponding author.
*E-mail address:* tengwu@buffalo.edu (T. Wu).

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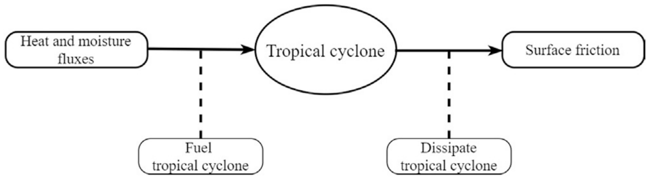

**Fig. 1.** Major processes governing tropical cyclone intensity.

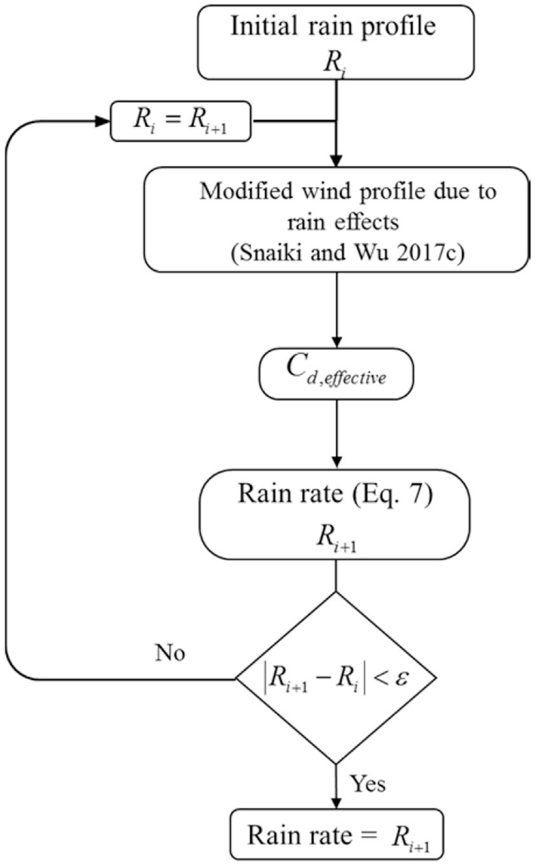

**Fig. 2.** Flow chart of the rain intensity simulation methodology.

winds and then decayed exponentially. According to the hurricane intensities grouped into three categories, i.e., tropical storms, category 1–2 tropical cyclones, and category 3–5 tropical cyclones, different radial variations of the rain rate were obtained. Based on the findings from Lonfat et al. (2004) together with the surface rain gauge data, Tuleya et al. (2007) proposed the Rainfall Climatology and Persistence (R-CLIPER) model. In this parametric model, the rain rate presented a Rankine-like profile with a linear variation from the tropical cyclone center to the radius of maximum rain rate, followed by an exponential decay. In addition, it has been proved using the findings of Kaplan and DeMaria (1995) that the hurricane rain rates and wind speeds are always highly correlated before/after landfall. While the R-CLIPER model could be employed over both the ocean and land, it assumed a symmetric distribution of the rain rate inside the tropical cyclone. Lonfat et al. (2007) improved the spatial variation of the rain field by introducing a modified version of the R-CLIPER model known as the Parametric Hurricane Rainfall Model (PHRaM) with consideration of the wind shear effects. However, both the R-CLIPER and PHRaM models were found to underestimate the maximum rain rate since they are based on the ensemble averages of numerous hurricanes (Tuleya et al., 2007).

Very few physics-based rain rate models have been introduced in the technical literature. In the theoretical model proposed by Langousis and Veneziano (2009a), it is assumed that all the upward moisture flux at the top of the tropical cyclone boundary layer is converted into rainfall. The vertical moisture flux was evaluated from the vertical winds at a reference height, generated by a modified version of the wind field model proposed by Smith (1968), along with the depth-averaged temperature

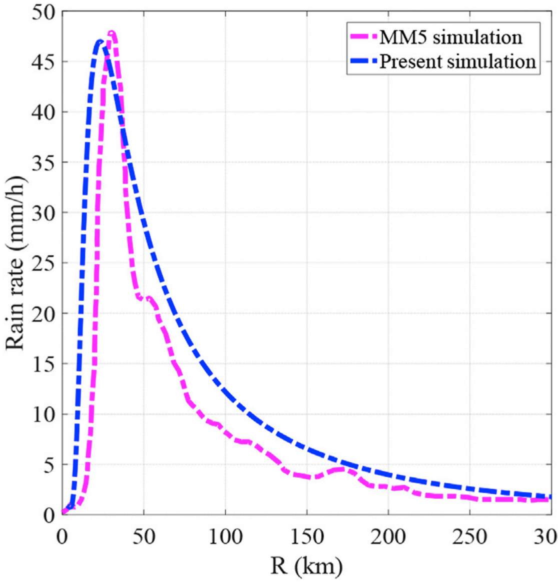

**Fig. 3.** Comparison of the azimuthally-averaged, rain-rate radial profile of Hurricane Frances.

**Table 1**
Tropical cyclones characteristics of the selected 12 rain fields.

| Mon\|Day\|h | Hurricane Center | | Storm Speed | Storm Direction | $V_{max}$ | $\Delta p$ | $R_{max}$ |
|---|---|---|---|---|---|---|---|
| | Latitude | Longitude | | | | | |
| | (deg) | (deg) | (m/s) | (deg) | (m/s) | (hpa) | (km) |
| 08\|29\|00 | 18.1 | −52.9 | 4.0 | 145 | 59.2 | 948 | 31 |
| 08\|29\|06 | 18.4 | −53.6 | 3.8 | 156 | 59.2 | 948 | 31 |
| 08\|29\|12 | 18.6 | −54.4 | 4.0 | 165 | 59.2 | 948 | 31 |
| 08\|29\|18 | 18.8 | −55.0 | 3.5 | 161 | 56.6 | 948 | 31 |
| 08\|30\|00 | 18.9 | −55.8 | 3.9 | 172 | 54.0 | 954 | 32 |
| 08\|30\|06 | 19.0 | −56.8 | 4.9 | 174 | 51.4 | 958 | 33 |
| 08\|30\|12 | 19.2 | −58.1 | 6.4 | 171 | 51.4 | 956 | 33 |
| 08\|30\|18 | 19.4 | −59.3 | 5.9 | 170 | 56.6 | 948 | 31 |
| 08\|31\|00 | 19.6 | −60.7 | 6.9 | 171 | 56.6 | 946 | 31 |
| 08\|31\|06 | 19.8 | −62.1 | 6.9 | 171 | 59.2 | 950 | 32 |
| 08\|31\|12 | 20.0 | −63.5 | 6.9 | 171 | 61.7 | 949 | 32 |
| 08\|31\|18 | 20.3 | −65.0 | 7.4 | 168 | 64.3 | 942 | 30 |