Title:
THEORETICAL ESTIMATION OF THE MEAN RAINFALL FIELD IN TROPICAL CYCLONES: AXI-SYMMETRIC COMPONENT AND ASYMMETRY DUE TO MOTION

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We develop a simple theoretical model for the mean rainfall intensity field in tropical cyclones (TCs). The model estimates the axi-symmetric rainfall profile $I_{sym}(r)$ as well as the asymmetric component due to storm motion $I_{mot}(r,\theta)$, where r is the radial distance from the TC center and θ is the azimuth relative to the direction of the storm. The model is parameterized in terms of the characteristics $\boldsymbol{\beta} = [S, T, V_c, C_d, V_{max}, R_{max}, B]^T$ of the TC, where T and S are, respectively, the average temperature and saturation ratio inside the TC boundary layer, V_c is the translation velocity of the storm, C_d is a surface drag coefficient (i.e. $1/C_d$=0 for non-slip conditions at the surface boundary), and V_{max}, R_{max}, and B are parameters that determine the shape and magnitude of the tangential wind velocity away from the surface boundary. Currently, the model does not include asymmetries due to wind shear, coastline geometry and topography, or fluctuations associated with rainbands and small-scale convection; hence its main use is to provide large-scale rainfall estimates.

Rainfall intensity is estimated as the vertical outflow of water vapor at the top of the TC boundary layer (BL). This upward-directed water vapor flux originates from the boundary layer horizontal inflow that turns upwards before it reaches the low pressure center. The analysis combines Holland's (1980) (or any other) tangential wind profile, an Ekman-type solution for the horizontal wind profiles inside the TC boundary layer, and moist air thermodynamics.

The BL solution for horizontal winds is based on Smith's (1968) formulation, which is modified to account for the effects of storm motion and solved using the Karman and Polhlausen momentum integral method. The vertical wind velocity at the top of the tropical cyclone boundary layer is calculated by vertical integration of the continuity equation using the obtained horizontal wind profiles. The axi-symmetric rainrate $I_{sym}(r)$ is zero for $r = 0$, increases to a maximum I_{max} at a distance R_{rain} somewhat smaller than R_{max} and then decays to zero in an approximately power-law way. Model results are compared to those from other studies (Shapiro, 1983; Kepert, 2001; Kepert and Wang, 2001). The three formulations are generally in good agreement for both horizontal and vertical fluxes, except for close to the storm center where nonlinear effects are dominant and Kepert's (2001) solution is less accurate and for the far-field where both the Shapiro (1983) and Kepert and Wang (2001) approaches are affected by numerical instabilities. The present scheme is computationally very efficient and stable also under inertially neutral conditions and for high storm translation velocities.

In a parametric analysis, we study how the symmetric component and the motion-induced asymmetries of rainfall depend on TC characteristics such as the maximum tangential wind velocity V_{max}, the radius of maximum winds R_{max}, Holland's B parameter, the surface drag coefficient C_d and the temperature T in the boundary layer. We find that more intense cyclones have higher I_{max} and lower R_{rain}. The symmetric rainfall profile, $I_{sym}(r)$, is insensitive to the selection of the surface drag, except for very small values of C_d (i.e. $C_d < 10^{-3}$). Also, the pickness of the tangential wind velocity profile, expressed through Holland's B parameter, has insignificant effects on the $I_{sym}(r)$ profile. More intense cyclones have higher I_{max} and lower R_{rain}. These theoretical findings are in agreement with empirical observations. The model shows that when cyclones in the Northern hemisphere move, their mean rainrate intensifies in the north-east quadrant relative to the direction of motion and de-intensifies in the south-west quadrant. The asymmetry is concentrated near the TC center and is stronger for less intense and faster-moving storms.

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Boundary layer
Storm motion