ABSTRACT

Numerical simulations of tropical cyclones using the Weather Research and Forecasting model are routinely evaluated against track and minimum sea-level pressure, metrics that collapse a three-dimensional physical system into two scalar quantities. This study argues that such bulk validation is insufficient and presents a multiscale microphysical evaluation of Extremely Severe Cyclonic Storm Fani over the Bay of Bengal using WRF-ARW version 4.6.1 at convection-permitting resolution. A triple-nested configuration with a 3 km cloud-resolving moving nest was employed, with ERA5 reanalysis as initial and boundary forcing. Prior to comparing microphysics schemes, a four-run cumulus and ocean coupling sensitivity study was conducted on the 9 km grey-zone domain. The Multi-Scale Kain-Fritsch scheme, which has not previously been applied to Bay of Bengal tropical cyclones, was found to be necessary to prevent spurious track deflection that caused the standard Kain-Fritsch scheme to fail landfall entirely. With this baseline established, the single-moment WSM6 scheme and the partially double-moment Thompson scheme were compared on the innermost domain. Although both schemes reproduced similar track trajectories and peak intensity within acceptable error margins, their internal physical architectures diverged substantially. WSM6 produced a deep, vertically extended warm core anomaly penetrating well below the melting layer, driven by concentrated mid-level latent heat release from aggressive graupel production. Thompson generated a compact, elevated warm core bounded above the melting layer, consistent with a snow-dominated heating profile. Radial partitioning of column-integrated frozen water paths across the eyewall, inner rainband, and outer rainband confirmed that WSM6 concentrates frozen mass tightly in the inner core while Thompson distributes a substantially larger snow mass across the outer storm. These structural differences were validated against a GPM Dual-frequency Precipitation Radar overpass on 01 May 2019, phase-locked to the observed storm latitude. WSM6 overestimated the 52 dBZ echo top height by approximately four kilometres relative to the GPM observation, a signature consistent with unphysical lofting of dense graupel by strong updrafts. Thompson placed the same threshold near 6.5 km, reproducing the observed melting-layer bright band and matching outer rainband echo tops to within 0.1 km. Taken together, these results demonstrate a coherent physical chain in which the microphysical phase preference of each scheme, graupel or snow, propagates through the thermodynamic core geometry, the hydrometeor mass distribution, and the three-dimensional dielectric structure of the storm, ultimately producing distinct impact footprints at landfall. The findings suggest that microphysics scheme selection carries structural consequences that surface metrics alone cannot reveal, and that observationally constrained three-dimensional validation using spaceborne radar is essential for credible convection-permitting tropical cyclone simulation.