Reply to "Comment on 'Marathon versus Sprint: Two Modes of Tropical Cyclone Rapid Intensification in a Global Convection-Permitting Simulation'"

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ABSTRACT: This reply addresses the comments by Montgomery and Smith on "Marathon versus sprint: Two modes of tropical cyclone rapid intensification in a global convection-permitting simulation."

KEYWORDS: Dynamics; Intensification; Tropical cyclones; Thermodynamics

In their comment, Montgomery and Smith (2025, hereafter MS25) critique some statements made by Judt et al. (2023, hereafter JRB23) about the rapid intensification (RI) of tropical cyclones. The primary goal of JRB23 was to document two distinct RI modes—termed "marathon" and "sprint"—which differ in the rate and duration of intensification, as well as in associated structural changes and environmental conditions. JRB23 acknowledged that these modes represent "opposite ends of a spectrum" and can "overlap" in some cases, emphasizing that they should not be treated as rigid categories. MS25's critique primarily focused on a few sentences in the introduction and conclusion sections of JRB23 that used the words "process" and "mechanism." We view their concerns regarding these sentences as mainly semantic. In response, we reiterate below, with revised wording, that the marathon and sprint modes involve distinct sequences of events that can aid in explaining and predicting RI cases. MS25 also argue that all tropical cyclone intensification events are ultimately driven by well-understood kinematic processes common to all tropical cyclones and that the lack of predictability of deep convection explains why RI is so difficult to forecast. We agree on some of their points, but we take this opportunity to clarify the distinct thermodynamic conditions with the marathon and sprint events analyzed by JRB23.

MS25's main argument is that there is "nothing really different dynamically within the broad picture" of tropical cyclone intensification in the marathon cases as compared to the sprint cases. If they had used the word "kinematically" instead of "dynamically," then we might agree with this statement. But to us, the word dynamically (or "dynamics") invokes both kinematics and thermodynamics. In the case of thermodynamics, the two archetypes we identified in JRB23 are quite different. In support of this perspective, Fig. 1 shows vertical cross sections of azimuthally averaged angular momentum M and moist entropy s 24 h after RI onset. A key distinction between the two cases lies in the relationship between M and s. In the marathon RI case, the M and s contours within the eyewall region (around 30-km radius) are nearly vertical and closely aligned in the midlevels (2–8-km altitude), as illustrated in Fig. 1a, suggesting a state of approximate moist slantwise neutrality (Rotunno and Emanuel 1987). In contrast, the sprint RI case exhibits quasi-horizontal s contours above 2–3 km that are nearly orthogonal to the M contours (Fig. 1b), clearly indicating a departure from moist slantwise neutrality.

Peng et al. (2018, hereafter PRB18) discussed the relevance of these two different thermodynamic states, which were associated with two "phases" of intensification in their case. Our sprint RI case (Fig. 1a) is reminiscent of their phase I in which intensification occurs with transient bursts of convection. In contrast, PRB18's phase 2 is characterized by moist slantwise neutrality within and near the eyewall; in this case, the updrafts were not transient but rather existed continuously and moved inward progressively. PRB18 also concluded that the time-dependent theoretical model of Emanuel (2012) can qualitatively explain this stage of intensification. One might ask whether these two thermodynamic states "simply" lead to different convective organization, as argued by MS25. We argue that the different thermodynamic conditions underlie the different series of events (e.g., transient versus persistent intensification). Furthermore, one of these thermodynamic states facilitates the development of a practical[1] theoretical model for intensification (e.g., Emanuel 2012).

Moving now to the environment of tropical cyclones, JRB23 also showed that marathon and sprint RI cases evolved under notably different environmental conditions. Marathon RI cases experienced primarily favorable conditions such as relatively weak vertical wind shear and a moist midtroposphere. In contrast, sprint RI cases occurred under relatively strong vertical wind shear and dry air—environmental conditions that are traditionally deemed as "unfavorable" to TC intensification (e.g., Gray 1968). These distinct environmental conditions likely influence the different series of events leading to RI. As a matter of proof, the sprint RI case highlighted by JRB23 underwent a vortex reformation that is likely enabled by the asymmetric shear-induced convection and deep vortex stretching, as in Nguyen and Molinari (2015). In other words, the series of events before and during intensification are different, i.e., reformation of a low-level vortex (sprint) as compared to a gradual inward movement of a slantwise neutral state (marathon). In

[1] "Practical" is defined as "of, relating to, or manifested in practice or action: not theoretical or ideal" (Merriam-Webster 2024).

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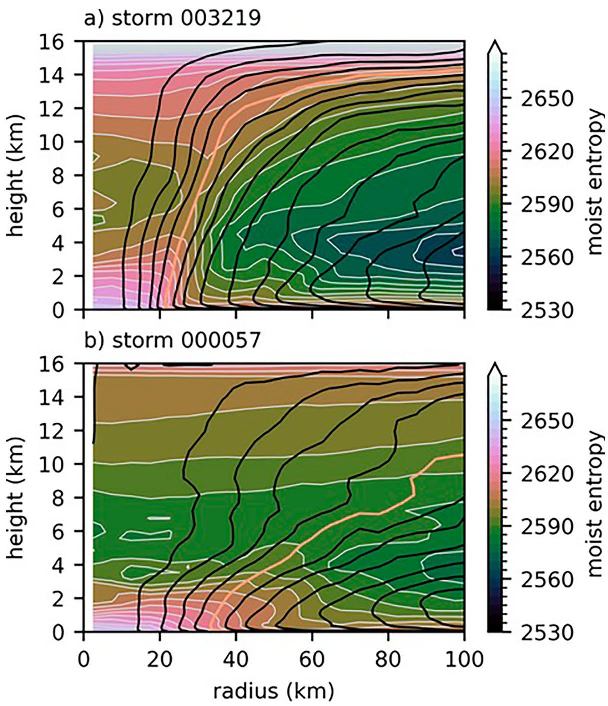

FIG. 1. Vertical cross sections of azimuthally averaged moist entropy (shading; J kg^{-1} K^{-1}) and absolute angular momentum (contours; interval of 2×10^5 m^2 s^{-1}) 24 h after the RI onset. The 10×10^5 m^2 s^{-1} isosurface is highlighted with a brown contour. (a) The marathon archetype from JRB23. (b) The sprint archetype.

our experience, cases with complex TC evolution, such as low-level vortex reformation, occur only when deep-layer wind shear is included in numerical simulations (Rios-Berrios et al. 2024 and references therein). The "prototype problem for tropical cyclone formation and intensification" noted by MS25 probably cannot produce such a series of events due to the lack of deep-layer wind shear.

To explain further, it might be helpful to build on the analogy introduced by MS25. We note that cars on a highway, indeed, move from point A to point B using the same underlying physics: an engine ultimately turns tires, which propels the car forward via contact with the road. MS25 noted that traffic plays a role in how quickly the car can accelerate. We add that the details of the car, its tires, and the state of the road (i.e., the car's environment) can matter a great deal as well. For example, if the road is wet, the car's acceleration will depend on the state of the tires, i.e., whether they have tread or not. As another example, if a recent earthquake cracked the road, an all-wheel drive vehicle may arrive at point B more quickly than a two-wheel drive vehicle. Even though the underlying physics is the same in all cases (as noted by MS25), certain details of a vehicle in relation to its environment clearly matter for specific explanations and/or predictions of the vehicle's acceleration. Analogously, we think the details of a tropical cyclone (i.e., its structure, including the thermodynamic state within the vortex) can be key to explanations and/or predictions of its intensification.

Finally, we explain why we studied cases of RI (the tail of the distribution of intensification events) in the study by JRB23. Simply put, tropical cyclone RI remains a forecasting challenge, for reasons that are unclear. As evidence, we point to this recent statement from Reinhart and Reinhart (2024): "Undoubtedly, the struggles of both the dynamical and statistical model guidance to anticipate Otis' historic RI will be the topic of future research."

We think that studies such as JRB23 contribute positively to this research effort.

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