Reply to RC1:

General comments:

This study implements direct radar reflectivity assimilation within MPAS-JEDI using multivariate background error covariance, improving heavy rainfall forecasts in the deep tropics. The authors demonstrate that the developed hybrid method propagates reflectivity information to thermodynamic and microphysical variables, enhances analysis accuracy, and outperforms ensemble-based methods, leading to better predictions of squall-line intensity, orientation, and precipitation, demonstrating the added value of multivariate correlations. The manuscript is generally well designed and written and should be interesting to the meteorological community. However, the evaluations show underprediction biases exist for these 12-h forecasts. Though this research includes several innovative contributions, the authors have not stated them well in the introduction section. So, some improvements are still needed before it can be accepted for publication. I suggest that the manuscript is accepted after major revisions.

Reply: We sincerely thank the reviewer for the careful and constructive evaluation of our manuscript and for recognizing the value of the developed direct radar reflectivity assimilation framework and its application to deep-tropical heavy-rainfall prediction. We appreciate the reviewer's comments regarding the underprediction biases in the forecasts and the need to better articulate the innovative aspects of the study in the Introduction. We have carefully considered all of these comments and have revised the manuscript accordingly. Detailed point-by-point responses to each comment are provided below.

Specific comments:

Based on Figure 9, 11, 12, and 13, all forecasts, especially for reflectivity threshold greater than 20 dBZ, have under-forecast biases. Given the high frequency of radar data, I wonder if the authors can try to assimilate the radial velocity and reflectivity data every 30 minutes, or even 15 minutes. Doing this could improve the forecasts and their quality.

Reply: We agree with the reviewer that under-forecasting biases are present, and we have added related statements in Section 5.2.2 to highlight this issue. We also thank the reviewer for this insightful comment and suggestion, which helps us further consider ways to improve the effectiveness of radar DA. We agree that a higher frequency of radar DA (e.g., every 15 or 30 min) could potentially better capture the rapid evolution of convective systems and help alleviate the under-forecasting issue. The primary focus of this manuscript, however, is to illustrate the implementation of direct reflectivity assimilation in MPAS-JEDI and to evaluate its performance, including the added value of the multivariate background error covariance and outer-loop update of reflectivity. We therefore leave the investigation of sub-hourly radar DA to future work, and we have added this as a future-work item in the Conclusion section.

The key innovative contributions of this research include (1) implementing direct reflectivity assimilation in MPAS-JEDI, (2) introducing multivariate static BEC relationships between ZH and thermodynamic/hydrometeor variables, (3) updating reflectivity from analyzed hydrometeors between outer loops, (4) evaluating this framework in a deep-tropical heavy-rainfall environment.

However, the authors have only discussed the first point clearly near the end of the Introduction. It is better to state all of them there.

Reply: We thank the reviewer for this valuable and constructive comment. We agree that the key contributions of this study were not clearly presented together, with only the first point being discussed in the Introduction. In response, we have substantially revised the Introduction to highlight the implementation of direct reflectivity DA in MPAS-JEDI, the multivariate static BEC, the outer-loop reflectivity update, and the evaluation of the framework in a deep-tropical environment. We hope that these revisions provide a clearer description of the key innovative contributions of this study.

Line 66-67: It is better to change "a next generation DA system specific for the Model …" to "a next generation DA system developed specifically for the Model…".

Reply: Fixed.

Line 77: "validates it" should be "validates them".

Reply: Fixed.

Line 233-235: It is better to add locations of two radars to Fig 1(a) and the areas they covered.

Reply: The two radar sites and their coverage have been added in Fig. 1a.

Line 237-242: It is better to mention which type of forward operator for reflectivity is used.

Reply: Since reflectivity is included as a model state variable in MPAS and an analysis variable of MPAS-JEDI, the observation operator is simply an interpolation operator from the MPAS model grid to the radar observation locations, rather than a complex nonlinear reflectivity operator. During the outer-loop update, however, we use the nonlinear reflectivity operator from the WSM6 microphysics scheme in MPAS to update the reflectivity state based on the analyzed hydrometeor variables. We have revised Section 2.4 to provide additional details on the reflectivity operator of the WSM6 scheme.

Line 264: Spelling out "HRES"

Reply: Fixed.

Line 269: Change "every 3 hours **util** $T + 18$" to "every 3 hours **until** $T + 18$".

Reply: Fixed.

Line 311: It is better to replace "Subsequentially" to "subsequently".

Reply: Fixed.

Line 317: Looks like “are shown in **4**..." should be “are shown in **Fig. 3**...".

Reply: Fixed.

Line 337-338: This sentence looks awkward. "correlations ... are generally positively correlated". Please reword.

Reply: Fixed.

Line 365: Should “6g” be “Fig. 5g”?

Reply: It is Fig. 5g. Fixed.

Line 370-372: Please reword this sentence.

Reply: Thanks! We have revised it to “As expected, the analysis increments of all three variables in HybB exhibit a hybrid structure, combining the smooth patterns of StaB with some of the flow-dependent features of EnsB; their magnitudes generally lie between those of StaB and EnsB (Figs. 5c, f, i)”.

Line 431: Two “and” in this sentence.

Reply: Fixed.

Line 438: Change “Scores were **aggerated** over four…” to “Scores were **aggregated** over four…”.

Reply: Fixed.

Line 447: Change “…suggest **imsufficient** ensemble…” to “…suggest **insufficient** ensemble…”.

Reply: Fixed.

Line 459: Change “…a improvement…” to “…an improvement…”.

Reply: Fixed.

Line 519: Change “**hydrometeors** variables” to “**hydrometeor** variables”.

Reply: Fixed.

Line 458-460: As stated in line 456, Figure 11 represents 1-12 hour forecasts, not simply at the 12-h forecasting lead time. So it is better to change the second half of the sentence to “"...particularly at the longer forecast lead times."

Reply: Fixed.