Dear Editors and Reviewers:

We deeply appreciate your helpful comments and suggestions, which enabled us to improve the quality of our present study. We have made revisions and replied to all the comments. Please find the point-by-point responses to the comments below. The comments are given below in black, our responses are in blue, and proposed changes to the manuscript are in red.

Reply to Reviewer #3:

1. Fig. 8:(1) Suggest adding the 95% significance area of the differences to the figure. Similarly, for all other relevant figures,

Response:

Thank you for your suggestion. To the best of the authors' knowledge, the t-test is commonly used to assess the significance of differences between two independent samples. In previous studies, the difference in mean RMSE was evaluated for statistical significance using a t-test, based on two independent sample sets, each comprising a large number of RMSE values (Lei and Anderson, 2014a; Privé et al., 2014).

As an initial study primarily focused on the direct variational assimilation of GMWR data, the assimilation was limited to clear-sky conditions. All experiments were conducted over a ten-day period from 13 to 22 October 2023. Among the available GMWR observations from August to October 2023, this period exhibited a notably higher frequency of clear-sky data, which was more favorable for demonstrating the role and potential of GMWR assimilation.

In Privé et al. (2014), the RMSE difference profile was calculated by averaging RMSE values from different analysis times over a two-month OSSE experiment. As a result, a large number of RMSE values were available, allowing for the application of a t-test. However, in this study, RMSE was computed over all analysis times as a single aggregated value, rather than being calculated at each analysis time. Therefore, a t-test could not be performed due to the lack of multiple independent samples. On the other hand, due to the limited number of experiments, even if RMSE were calculated at each analysis time, only 10

samples would be available, which could render the test results volatile and statistically unreliable. The all-sky assimilation technique will be the focus of our upcoming study, in which GMWRs from cloudy regions will also be assimilated. At that stage, three-month experiments will be conducted, which will provide a sufficiently large number of samples to enable statistical significance testing of RMSE differences.

Lei, L., and J. L. Anderson, 2014a: Empirical Localization of Observations for Serial Ensemble Kalman Filter Data Assimilation in an Atmospheric General Circulation Model, https://doi.org/10.1175/MWR-D-13-00288.1.

——, and ——, 2014b: Impacts of Frequent Assimilation of Surface Pressure Observations on Atmospheric Analyses, https://doi.org/10.1175/MWR-D-14-00097.1.

Privé, N. C., R. M. Errico, and K.-S. Tai, 2014: The Impact of Increased Frequency of Rawinsonde Observations on Forecast Skill Investigated with an Observing System Simulation Experiment, https://doi.org/10.1175/MWR-D-13-00237.1.

2. (2) It is clear that the MWR data assimilation mostly brings negative impacts to the wind fields. The manuscript needs to cover this fact. The reason for the degradation, as mentioned in the manuscript, may be that the background error covariance does not spread the observation information to the wind field well. Using ensemble covariance may mitigate this.

Response:

In the verification of the initial conditions against radiosonde observations, the assimilation of GMWR data generally exhibits a negative impact on the wind fields. In 3DVAR, the adjoint of RTTOV-gb only updates temperature and humidity in observation space, while adjustments to the wind fields rely on the background error covariance. This suggests that the background error covariance may be a contributing factor to the negative impact on wind field analysis. Therefore, improving the background error covariance (e.g., by incorporating

ensemble-based covariances) could potentially mitigate this limitation. As an initial study primarily focused on the direct variational assimilation of GMWR data with machine learning-based bias correction, it is admitted that this study has some limitations. The MWR assimilation was implemented only using 3DVAR, based on RTTOV-gb and WRFDA. Future work could explore the implementation of MWR assimilation using EnVar, EnKF, or 4DVAR.

The negative impacts to the wind fields has been cover in the results and discussion section of the manuscript, as shown below.

"It is noted that the GMWR assimilation has negative impacts on the wind fields. The RMSE for zonal and meridional winds exhibits a slight negative effect when GMWR is assimilated, with meridional winds even showing an increase in RMSE."

"However, it should be noted that the assimilation of GMWR data generally has a negative impact on the wind fields in the initial conditions. The background error covariance may contribute to this negative impact, as it determines the response of the wind fields to the adjustments in temperature and humidity made by RTTOV-gb. As an initial study primarily focused on the direct variational assimilation of GMWR data with machine learning-based bias correction, it is admitted that this study has some limitations. The GMWR assimilation was implemented using 3DVAR, based on RTTOV-gb and WRFDA, and only static background-error covariances were employed in this study. The background error covariance matrix plays an important role in variational data assimilation, but this type of covariance is climatological, spatially homogeneous, and isotropic. This may limit the impact of GMWR assimilation, and flow-dependent error covariances should be considered in future work."

3. Figures: Suggest adding the time period, when each figures are generated, to the figure captions.

Response:

Added.

4. Figure 10: This figure shows verifications against surface station observations, right? Suggest changing "station observations" to "surface stations observations", changing subplot titles to "2m Temperature", etc.

Response:

This figure and the corresponding text have been revised

5. Line 328-329: "the nagavife RMSE differences gradually increase" -> "the RMSE reduction gradually decreases"

Response:

Corrected

6. Line 330: The RMS difference "decreases" instead of "increases". Consider revising accordingly for all relevant parts.

Response:

The corresponding text have been revised

7. Fig. 10b: The manuscript is expected to cover the fact that the verification against the surface RH field shows a negative impact from the MWR data assimilation after 12h and explain why.

Response:

In the verification against surface station observations, the improvement in RH due to GMWR assimilation gradually decreases with increasing lead time and becomes negative after 12 hours. Several factors may be responsible. On one hand, in the verification of initial conditions against radiosonde observations, the assimilation of GMWR data generally exerts a negative impact on the wind fields. The degradation in wind fields may, through model processes, affect the relative humidity. In addition, the model is highly nonlinear, and its errors do not evolve linearly.

However, the evolution of model errors is complex and difficult to investigate. As this study primarily focuses on the implementation of variational direct assimilation of GMWR data with nonlinear bias correction and provides a

preliminary assessment of its potential impact, the cause of the negative impact on relative humidity after 12 hours will be addressed in detail in future study.

Thanks to the reviewer's suggestion, we have covered this fact in the manuscript as following.

“Similar results are observed for relative humidity, where the RMSE reduction also decreases and approaches zero at a lead time of 12 hours. GMWR_1H consistently demonstrates the largest RMSE reduction for relative humidity. However, it should be noted that the direct assimilation of GMWR data caused a negative impact on relative humidity at a lead time of 12 hours. The degradation of wind fields (Fig. 9) and the model’s inherent nonlinearity may be responsible.”

8. Line 338-339: "likely due to a gradual increase in model error". This is not accurate, as this happens to both CNTL and MWR.

Response:

As integration time increases, systematic model errors accumulate. The atmosphere is highly nonlinear, and initial and model errors may not combine linearly, potentially filtering out improvements in the initial state. In addition, the assimilation algorithm is imperfect and does not improve all variables across all regions (e.g., the wind field shown in Fig. 9), while multivariate interactions may further diminish the overall effect. The explanation previously provided in the manuscript may not be sufficiently accurate. As this aspect is not the focus of this study, this sentence has been removed to avoid potential misinterpretation.

9. Line 342: "can further improve forecasts" -> "can further improve the short-term forecasts".

Response:

Corrected

10. Line 362-366: "This may be attributed to … the first 12 hours". This logic in this part does not read good, and it looks like they can be removed.

Response:

We appreciate the reviewer's comment and agree that the original sentence lacked clarity and was prone to misinterpretation. The primary point we intended to convey is that the relatively limited improvements observed in the figure could be related to the long forecast lead times (12 and 24 hours), during which model errors tend to accumulate and diminish the benefits of improved initial conditions provided by GMWR assimilation. The sentences have been revised as follows:

"The limited improvement shown in this figure could be related to the relatively long forecast lead times (12 and 24 hours), during which model errors tend to accumulate and weaken the benefits of improved initial conditions from GMWR assimilation. Verification against surface station observations indicates that the improvements were primarily confined to the first few hours, particularly for temperature and humidity. After 12 hours, the impact declined noticeably, with some cases even exhibiting negative effects (Fig. 11)."

11. There are quite a few locations where articles "the/a" are missing (some of them are mentioned below). Consider a thorough proofreading of the manuscript.

Response:

We have thoroughly proofread the manuscript and corrected all identified instances where articles ("the/a") were missing. We also performed an additional grammar check to ensure clarity and correctness throughout the text.

Edits:

12. Line 50: The first appearance of "RTTOV", please define this acronym.

Response:

The full name of RTTOV has been defined at its first occurrence in the revised manuscript.

13. Fig. 1: The legend says "SOUND", suggest changing to "SONDE" or "SOUNDING"

Response:

Corrected. The legend label has been changed from "SOUND" to " SONDE".

14. Line 73: remove "Similarly, "

Response:

Corrected.

15. Line 105: change to "into the radiance space"

Response:

Corrected.

16. Fig 2: Suggest removing the thumbnail figures in Fig. 2e and 2f; put the green lines into Fig. 2c and 2d

Response:

Corrected.

17. Fig. 116-157: Shortening this sentence to "an MWR direct assimilation module was developed within WRFDA"

Response:

Corrected.

18. Line232： change to "the above bias correction model,"

Response:

Corrected.

19. Line 354: "against station observations" -> "against surface station observations". Change other occurrences of "station observations" throughout the manuscript.

Response:

Revised as suggested. All instances of "station observations" have been changed to "surface station observations".

20. Line 416: "typically exceeds 700 hPa" -> "is typically lower than 700 hPa"

Response:

Corrected.

21. Line 429: "This type covariances" -> "This type of covariances"

Response:

Corrected.