Reply to Reviewer #2

We thank the reviewer for the careful reading of the manuscript and the constructive comments. The manuscript has been revised accordingly. Our point-by-point responses are provided below.

1. **Additional clarification of the dynamically estimated covariance matrices should be demonstrated.**

Re:

We thank the reviewer for this suggestion and agree that providing representative examples of the dynamically estimated covariance matrices can improve the transparency and physical interpretability of the proposed retrieval framework. Following the reviewer's recommendation, we have added a new Appendix A entitled "Kalman Filter–Derived P and R Matrices", which presents representative examples of the P and R diagnosed by the adaptive Kalman filter. The appendix includes Figure A1 and Figure A2, showing the covariance structures derived from all precipitation cases used in this study, together with a comparison of their vertical correlation characteristics under different precipitation intensity categories.

To guide readers to these additional analyses, we have also added the following statement in Lines 240–244 of the revised manuscript: "To provide further insight into the diagnosed error covariance characteristics, Appendix A presents representative R and P matrices (Figure A1 and A2) derived from all precipitation cases used in this study, including a comparison of their vertical correlation structures under different precipitation intensity categories."

The content of Appendix A is attached below:

Figure A1 presents the R matrices diagnosed during the water vapor profile retrieval process using all precipitation cases listed in Table 3. The results reveal substantial differences in the structure of the diagnosed R matrices across precipitation intensity categories, indicating that the characteristics of observation errors vary with the rainfall environment. For cases associated with hourly accumulated precipitation between 10 and 20 mm (Figure A1a), a pronounced vertical correlation is evident, with the strongest correlated region extending approximately from 900 to 1600 m above ground level. In contrast, the cases with hourly precipitation between 20 and 30 mm (Figure A1b) exhibit relatively weak vertical correlations, and no distinct coherent correlation structure can be identified. For the most intense precipitation cases, characterized by hourly accumulations exceeding 30 mm (Figure A1c), the enhanced vertical correlations are primarily confined to the lower atmosphere, with the largest values concentrated between 150 and 600 m.

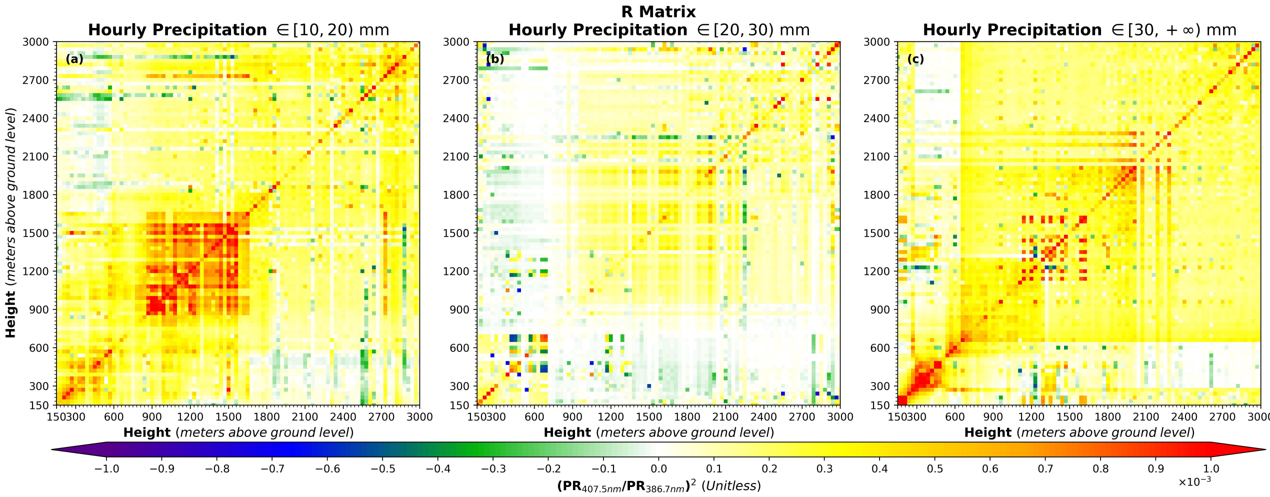

Figure A1. R matrices for water vapor profile retrievals derived from all precipitation cases listed in Table 3. Panels (a), (b), and (c) correspond to cases with hourly accumulated precipitation of 10–20 mm, 20–30 mm, and >30 mm, respectively.

Figure A2 presents the P matrices diagnosed during the water vapor profile retrieval process for all precipitation cases listed in Table 3. Compared with the R matrices shown in Figure A1, the diagnosed P matrices display much weaker vertical correlations, with no pronounced coherent correlation structures evident in any of the precipitation categories. Furthermore, the overall covariance patterns are largely consistent among cases with hourly accumulated precipitation of 10–20 mm (Figure A2a), 20–30 mm (Figure A2b), and greater than 30 mm (Figure A2c).

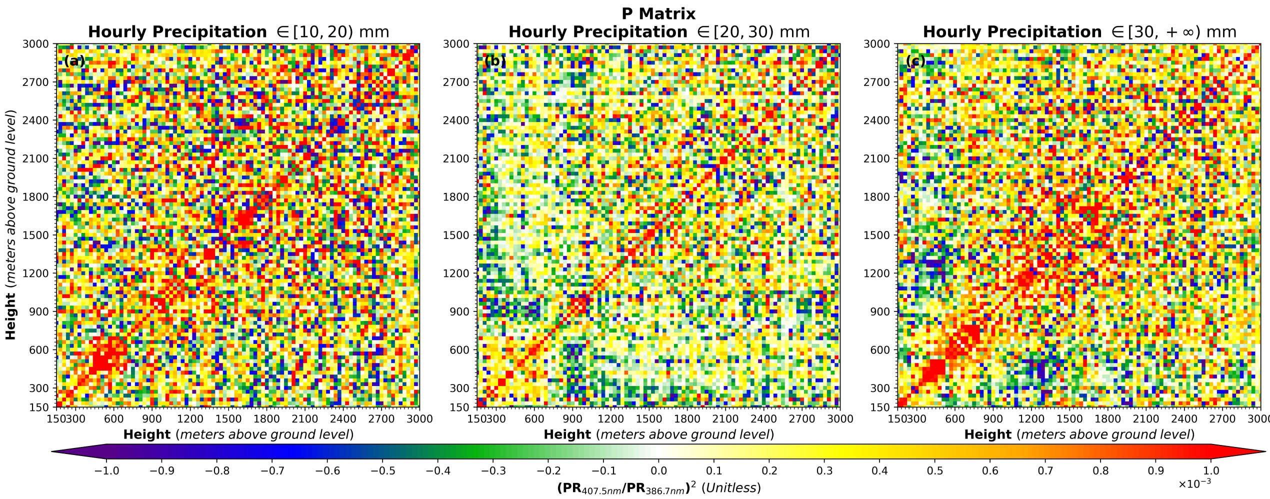

Figure A2. P matrices diagnosed during the water vapor profile retrieval process for all precipitation cases listed in Table 3. Panels (a), (b), and (c) correspond to cases with hourly accumulated precipitation of 10–20 mm, 20–30 mm, and >30 mm, respectively.

2. The interpretation of the innovation-based diagnostic metric should be clarified further.

Re:

We thank the reviewer for this suggestion. In response to this comment, we have revised the manuscript to more explicitly emphasize the framework-dependent nature of the IFR and to clarify that it should not be interpreted as a rigorous information-theoretic quantity or a direct measure of absolute information content. The revised description also strengthens the statement that the IFR is intended strictly for qualitative and comparative diagnostic purposes within the TCKF1D-Var framework, and that caution should be exercised when generalizing this metric beyond the specific retrieval system used in this study.

Specifically, Lines 304–308 have been revised as follows: “It should be noted that the IFR defined in this study is a diagnostic quantity that is inherently framework-dependent within the TCKF1D-Var system, rather than a rigorous information-theoretic measure. It does not represent formal information content in the sense of information theory, and therefore should not be interpreted as directly quantifying absolute information gain. Instead, the IFR is introduced as a qualitative indicator to describe the relative magnitude between observational constraints and forward model uncertainty, thereby providing a consistent basis for comparing different experimental configurations within the same retrieval framework. Accordingly, the interpretation of the IFR throughout this study is intentionally limited to comparative and diagnostic purposes, rather than quantitative assessment of information content. Care should therefore be taken when generalizing this metric beyond the specific retrieval system used in this work.”

3. **The interpretation of the pre-precipitation moisture structures need clarification.**

Re:

We thank the reviewer for this comment and agree that the interpretation of the retrieved moisture increments requires caution, particularly regarding the distinction between physical atmospheric evolution and adjustments to the background (ERA5) prior state.

In response to this suggestion, we have revised the manuscript to explicitly clarify that the analysis increments should be interpreted as a combination of observational constraints and corrections to the ERA5 prior field, rather than direct and independent confirmation of atmospheric moisture evolution. We further emphasize that part of the retrieved moistening signal may reflect potential biases in the ERA5 prior under convective boundary-layer conditions, and therefore the physical attribution of the increments has been moderated throughout the revised text.

Specifically, the corresponding discussion in the manuscript has been revised in Lines 389–395 to read: “However, it should be noted that the interpretation of the retrieved moistening signal requires caution, as part of the analysis increment may also represent corrections of potential ERA5 prior biases under convective boundary-layer conditions, rather than solely independent evidence of atmospheric moisture evolution. In this context, the increments should be interpreted primarily as retrieval-based adjustments relative to the prior state, rather than direct observational confirmation of physical moisture tendencies. To further examine the temporal behavior of the analysis increments, the time–height evolution of the mean analysis increment (Figure 7), defined as the difference between the TCKF1D-Var retrievals and the ERA5 prior profiles, is calculated using the cases summarized in Table 3. ”

4. **Physical interpretation of the precipitation-category-dependent structures need to be strengthened.**

Re:

We thank the reviewer for this suggestion. We agree that a more physically grounded interpretation of the precipitation-category-dependent structures can improve the scientific depth and broader meteorological relevance of the manuscript. In response to this comment, we have expanded the discussion in Section 4 by adding a new analysis based on precipitation-category composite increments, aiming to better link the observed statistical structures with their possible dynamical and observational controls. Specifically, we conducted additional composite analyses of the TCKF1D-Var retrieved water vapor mass mixing ratio analysis increments for the three precipitation intensity categories (10–20 mm, 20–30 mm, and ≥30 mm), as summarized in Table 3 and shown in the newly added Figure 11.

Specifically, the added section reads as follows:

Since all three representative cases exhibit substantial analysis increments relative to the ERA5 prior profiles, and the timing, vertical distribution, and magnitude of these increments appear to vary systematically with precipitation intensity, additional composite analyses were conducted for the three precipitation categories listed in Table 3. Specifically, composite analysis increments of the TCKF1D-Var retrieved water vapor mass mixing ratio profiles were calculated for the 10–20 mm, 20–30 mm, and ≥30 mm hourly accumulated precipitation groups to investigate their temporal–vertical evolution prior to precipitation onset (Figure 11). For the 10–20 mm precipitation category (Figure 11a), the analysis increments are generally negative below 900 m and positive above 900 m. During the final 90 min before precipitation onset, this vertically stratified structure becomes increasingly pronounced, indicating an enhanced vertical contrast in the moisture analysis increments prior to precipitation initiation. For the 20–30 mm precipitation category (Figure 11b), positive analysis increments are evident above 450 m during the period from 240 to 180 min before precipitation onset. During the subsequent 180–30 min period, the positive increments within the 1500–3000 m layer gradually transition into negative values, while the increments within the 450–1500 m layer remain positive but with substantially weaker magnitude. In contrast, the 300–450 m layer maintains persistently negative analysis increments throughout the entire pre-precipitation period, consistent with the characteristics identified for the 10–20 mm category. For the ≥30 mm precipitation category (Figure 11c), the analysis increments exhibit a pronounced structural transition approximately 120 min before precipitation onset. During the earlier stage (240–120 min prior to precipitation), the analysis increments are predominantly negative below 1200 m and positive above 1200 m. However, during the final 120 min before precipitation onset, the previously negative low-level increments transition into positive values, and their magnitude increases progressively as precipitation onset approaches. A similar temporal enhancement is also evident within the 1200–3000 m layer, although the increase is substantially stronger than that below 1200 m.

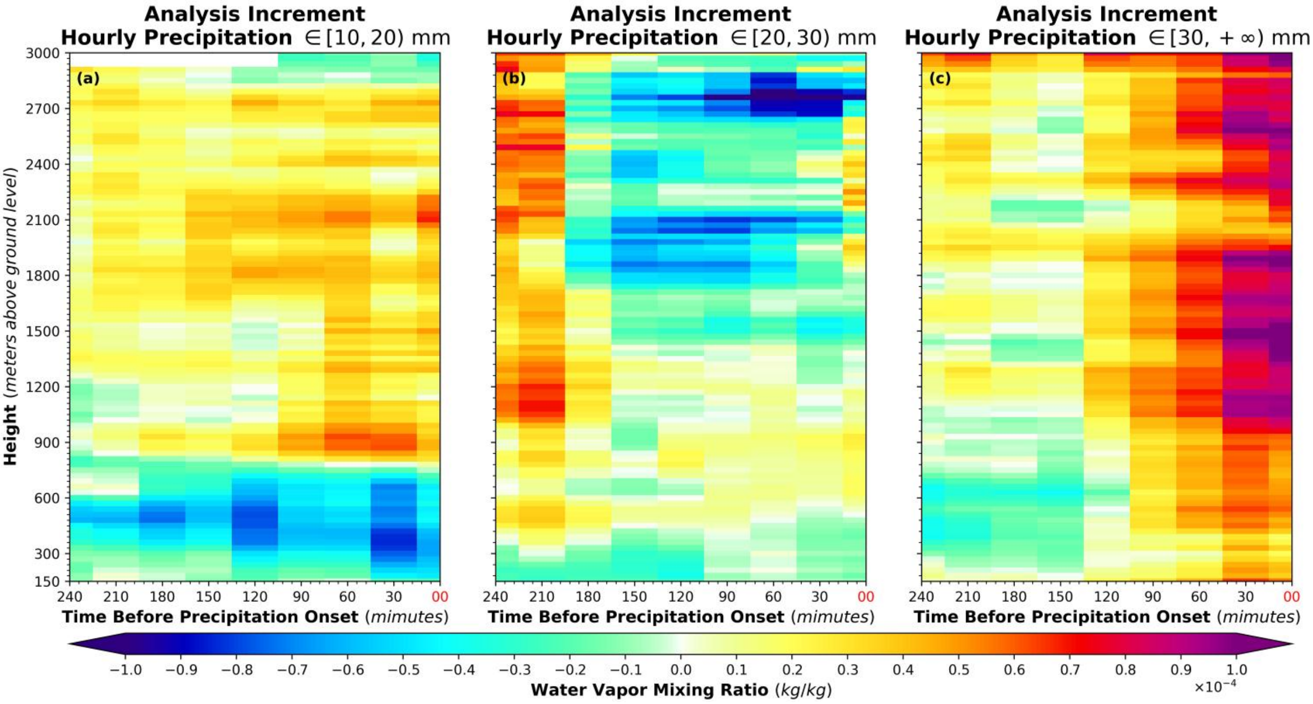

Figure 11: Temporal–vertical evolution of the case-averaged analysis increments in the TCKF1D-Var retrieved water vapor mass mixing ratio profiles relative to the ERA5 prior before the onset of nocturnal heavy precipitation for three hourly accumulated precipitation categories: (a) 10–20 mm, (b) 20–30 mm, and (c) ≥30 mm. The red-colored x-axis tick label (00 minutes) denotes the precipitation occurrence time.

Overall, these results demonstrate that the TCKF1D-Var retrieved water vapor mass mixing ratio profiles not only provide substantial adjustments relative to the ERA5 prior profiles, but also exhibit temporally and vertically coherent analysis increment structures prior to nocturnal heavy precipitation. More importantly, the evolution characteristics of these analysis increments appear to be systematically associated with precipitation intensity, as represented by the hourly accumulated precipitation amount.

5. **Figures 7–9 are informative. However, precipitation onset timing could still be indicated more explicitly within the figures themselves, rather than only in the text description.**

Re:

We thank the reviewer for this suggestion. We agree that marking the precipitation onset time within the figures improves clarity and facilitates easier interpretation of the temporal evolution presented in Figures 7–9. We have revised Figures 7–9 by explicitly indicating the precipitation onset time using a red-colored x-axis tick label. This visual marker allows readers to directly identify the onset timing within each figure without referring solely to the accompanying text description. In addition, we have updated the corresponding figure captions to clearly state that the red-colored tick label denotes the precipitation onset time.

6. **Please clarify more explicitly whether the reported 30 m vertical resolution refers to retrieval grid spacing, native lidar resolution, or effective retrieval resolution after filtering and inversion.**

Re:

We agree that the definition of the reported vertical resolution should be stated more explicitly to avoid potential ambiguity. In response to this comment, we have clarified in the revised manuscript that the 30 m vertical resolution refers to both the retrieval grid spacing and the native vertical resolution of the Raman lidar observations used in this study (Line 81). No additional vertical smoothing or degradation was applied beyond the original lidar measurement resolution during the inversion procedure. Therefore, the 30 m resolution can be regarded as consistent between the observation system and the retrieval discretization, rather than an effective resolution resulting from post-processing or filtering.

7. **The discussion regarding computational efficiency and operational applicability is useful, but a brief estimate of computational cost per retrieval cycle would further improve the practical relevance of the manuscript.**

   Re:

   We agree that information on computational cost would further improve the practical relevance of the study. However, we would like to clarify that in this study we did not perform a strictly controlled timing benchmark for the retrieval system. The overall runtime includes not only the computational steps of the TCKF1D-Var algorithm itself, but also data acquisition through API-based data access. This data access component is subject to variable network latency and bandwidth fluctuations, which introduces additional uncertainty into any precise timing statistics.

   The computations were conducted on a 2025 Apple Mac Studio equipped with an Apple M4 Max chip (16-core CPU and 40-core GPU) and 128 GB of RAM. Based on our best estimate from the full experimental workflow, the total processing time for all cases was approximately 20 days, corresponding to an average retrieval time of about 15 minutes per profile.

   Given the absence of a strictly controlled timing protocol and the influence of external data acquisition variability, we consider that reporting a precise computational cost per retrieval cycle may not be fully representative. Therefore, we have chosen not to include a detailed quantitative timing benchmark in the revised manuscript, while instead providing the above qualitative estimate in the response for transparency.

   We appreciate the reviewer's comment, which highlights the importance of operational applicability considerations in future work, particularly under a fully optimized and isolated computational environment.

8. **Some grammatical and stylistic issues remain throughout the text. Although none are severe, an additional language editing pass would improve readability. For example, "All authors delcare no competing interest" should be "All authors declare no competing interests", and "within boundary layer preceding" should include "the".**

   Re:

   Changed at Lines 325 and 580.

9. **The conclusions are generally balanced. However, several statements concerning future NWP assimilation applications may still benefit from slightly more cautious wording, given that no direct assimilation experiments are presented in the current study.**

   Re:

We agree that the statements related to potential numerical weather prediction assimilation applications should be expressed more cautiously, given that no direct data assimilation experiments are conducted in this study.

In response to this comment, we have revised the manuscript to explicitly clarify the exploratory nature of any potential NWP applications and to avoid any implication that assimilation performance has been evaluated within the present work. The revised section (Line 543–547) now reads: “Furthermore, the potential application of the retrieved water vapor mass mixing ratio profiles in data assimilation–numerical weather prediction systems may be explored in future studies. Such investigations would aim to assess the possible benefits of these retrievals for representing pre-convective moisture conditions in short-term forecasts and severe weather early warning, but require dedicated assimilation experiments that are beyond the scope of the present study.”