Reply to Reviewer #1

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. **Title is misleading. This study mainly retrieves water vapor profile prior to nocturnal heavy precipitation, not nocturnal water vapor profiles.**

   Re:

   We thank the reviewer for this helpful suggestion. The title has been revised to better reflect the scientific scope of the study. The new title is: "Extended TCKF1D-Var framework for Mie − Raman Lidar Boundary Layer Water Vapor Profiling: Insights into Nocturnal Preprecipitation Moisture Evolution."

2. **Line 20, please also note the number of events evaluated.**

   Re:

   We agree with the reviewer and have added the number of evaluated cases in the corresponding sentence. Lines 19 − 21 now read: "The method is evaluated against co-located radiosonde observations launched prior to nocturnal heavy precipitation events (224 cases in total) at 56 MRL − radiosonde co-located stations across China in 2025."

3. **Line 23, ERA5 prior profiles or ERA5 profiles?**

   Re:

   We thank the reviewer for pointing out this ambiguity. The sentence has been revised for clarity. Lines 21 − 24 now read: "The retrieved water vapor mass mixing ratio profiles, with a vertical resolution of 30 meters and a temporal resolution of 30 minutes, exhibit consistently reduced mean bias and root mean square error compared to ERA5 profiles as priori, with the largest improvements found in the 1.2 − 3.0 km layer."

4. **Line 28, "large hourly rainfall totals" needs to be rephrased.**

   Re:

   We thank the reviewer for this helpful suggestion. The phrase "large hourly rainfall totals" has been rephrased to improve clarity and scientific expression. The sentence now reads: "Nocturnal precipitation over China is frequently characterized by abrupt initiation, intense short-duration rainfall, and high societal impact (Luo et al., 2016 and 2020; Chen et al., 2021; Zhang et al., 2025a; Gao et al., 2026)."

5. **Line 35, again, 'during nighttime', or 'before sunset'?**

   Re:

   We agree with the reviewer and revised the wording to more accurately describe the scientific context. Lines 34 − 35 now read: "These features highlight the necessity of monitoring high-resolution temporal and vertical variations of boundary-layer water vapor prior to precipitation onset."

6. **Line 36, please add introduction to current observing systems used for fine scale moisture profiles and their detailed limitations. And in line 39, what limitation?**

Re:

We thank the reviewer for this valuable suggestion. In the revised manuscript, we have substantially expanded the discussion of existing observing systems used for fine-scale moisture profile measurements and clarified their respective limitations. Specifically, we now explicitly discuss the characteristics and limitations of conventional radiosondes, satellite-based infrared and microwave sounders. The revised text also clarifies what limitations are referred to in the original statement, including insufficient temporal sampling, coarse vertical resolution within the boundary layer, reduced sensitivity under cloudy conditions, and signal attenuation effects. The corresponding scentence (Line 35–40) has been revised as follows: "However, capturing such rapid and fine-scale moisture evolution remains challenging for existing observing systems: conventional radiosonde observations provide high-accuracy thermodynamic profiles but are typically limited by sparse temporal sampling; satellite-based infrared and microwave sounders offer broad spatial coverage, however, their vertical resolution and sensitivity within the planetary boundary layer are often insufficient, particularly under cloudy and precipitating conditions; ground-based microwave radiometers can provide continuous thermodynamic observations but generally suffer from relatively coarse vertical resolution and reduced retrieval accuracy near sharp moisture gradients. (Richter et al., 2026; Mayer et al., 2012; Oue et al., 2022; Wulfmeyer et al., 2008 and 2015)."

As well, Line 42 has been revised to: "Ground-based active remote sensing provides a promising pathway to address the limitations listed above."

7. **Some references are way too old.**

Re:

We assume the reviewer is referring to Vaughan et al. (1988). Although this reference is relatively old, it represents one of the pioneering and foundational studies on Raman lidar retrievals of atmospheric water vapor and temperature profiles. Many subsequent developments in Raman lidar thermodynamic profiling are directly based on this work. Therefore, we believe it is scientifically appropriate and historically important to retain this citation.

8. **Line 46, "a priori assumption" or "a priori requirement"?**

Re:

The wording has been revised according to the reviewer's suggestion. "Assumption" has been replaced with "requirement" in Line 51.

9. **Line 58, "Despite these advances"?**

Re:

We thank the reviewer for this helpful suggestion. We agree that the phrase "Despite these advances" may imply an unintended contrastive meaning in this context. Since the subsequent sentence aims to describe the operational configuration of the CMA Mie − Raman lidar network rather than a limitation or contradiction, the wording has been revised to improve the logical flow and readability. Specifically, “Despite these advances” has been replaced with “Within this measurement paradigm” (Line 63).

10. Line 102, did you mean measurement sensitivity by saying resolution?

Re:

We thank the reviewer for this important comment. According to the definition provided in the Guide to Instruments and Methods of Observation published by the World Meteorological Organization (WMO), “resolution” is defined as: “The smallest change in a quantity being measured that causes a perceptible change in the corresponding indication.” (WMO-No. 8, Volume I, page 17). Therefore, the original use of “resolution” is technically valid. However, the WMO guide further distinguishes between spatial resolution and scale resolution (page 24). In the context of this study, the intended meaning corresponds more specifically to scale resolution. Accordingly, the terminology in Section 2.2.1 has been revised from “resolution” to “scale resolution”.

Reference:

World Meteorological Organization (WMO): Guide to Instruments and Methods of Observation (WMO-No. 8), Volume I, Geneva, 2024, https://doi.org/10.59327/WMO/CIMO/1.

11. Line 2.2.2, “The Fifth…”. Also, it is suggested to change the title to: Atmospheric Priori.

Re:

The manuscript has been revised according to the reviewer’s suggestion.

12. Eq. 1 is unnecessary since it is a well known equation.

Re:

We agree that Eq. (1) is a classical and widely recognized thermodynamic equation for atmospheric science researchers. However, Atmospheric Measurement Techniques is an open-access interdisciplinary journal serving not only atmospheric scientists but also researchers from other disciplines and readers interested in cross-disciplinary scientific applications. Retaining this equation helps maintain the accessibility and readability of the manuscript for broader audiences who may not have formal atmospheric science backgrounds. Therefore, we prefer to retain Eq. (1) in the revised manuscript.

13. Since microwave instrument is also introduced in Fig. 2, it is necessary to give a brief introduction to this dataset and the purpose of this dataset in this study.

Re:

We appreciate the reviewer’s suggestion. As the present manuscript represents the latest development of the TCKF1D-Var research framework, we consider it necessary to briefly introduce previous related system configurations, including the microwave instrument shown in Figure 2, in order to clearly highlight the methodological evolution and distinguish the present work from earlier studies. This organization is intended to help readers efficiently understand the scientific narrative and improve the continuity between the current and previous TCKF1D-Var studies.

14. Please rephrase the title of section 3.1&3.2

Re:

The section titles have been revised as follows: Section 3.1, from "Retrieval temporal resolution selection" to "Sensitivity of Retrieval Performance to Temporal Resolution"; Section 3.2: from "Thermodynamic profile general performance" to "Evaluation of Retrieved Thermodynamic Profiles".

15. Line 322, the definition of heavy rainfall here is not proper. Extreme rainfall events were identified using the 99th percentile, this method accounted the local climatological features. So, why the identification of heavy rainfall uses another approach? To expand your sample set, you can define heavy rainfall using the 95th or 90th percentile.

Re:

We thank the reviewer for this thoughtful suggestion. We agree that percentile-based thresholds are effective in accounting for regional climatological characteristics. In the present study, however, the 99th percentile criterion was intentionally adopted to focus specifically on the most extreme nocturnal precipitation events, following methodologies widely used in previous extreme precipitation studies over China (e.g., Zheng et al., 2016; Yin et al., 2018; Feng et al., 2023). Therefore, we prefer to retain the current definition in order to maintain consistency with the existing literature and to preserve the focus of this study on the most intense precipitation cases.

References:

Zheng, Y., Xue, M., Li, B. et al.:Spatial characteristics of extreme rainfall over China with hourly through 24-hour accumulation periods based on national-level hourly rain gauge data. Adv. Atmos. Sci. 33, 1218 – 1232, https://doi.org/10.1007/s00376-016-6128-5, 2016.

Ma Q, Lei H, Jia F, Sun S, Yan P, Gu Y and Feng G.: Interannual variability of extreme precipitation in late summer over west China during 1961 – 2021. Front. Environ. Sci. 11:1185776, https://doi.org/10.3389/fenvs.2023.1185776, 2023.

Wu, X., Guo, S., Yin, J., Yang, G., Zhong, Y., and Liu, D.: On the event-based extreme precipitation across China: Time distribution patterns, trends, and return levels. J. hydrol., 562, 305-317. https://doi.org/10.1016/j.jhydrol.2018.05.028, 2018.

16. Line 325-328, what is the purpose of analyzing these differences?

Re:

The corresponding text is intended to provide a concise summary and interpretation of the statistical information presented in Table 3, thereby helping readers rapidly understand the key characteristics of the results before examining the detailed tabulated values. We believe such summary descriptions improve the readability of the manuscript.

17. Line 349, these three groups were not defined before.

Re:

The three groups were defined in Table 3 (Line 344). We have carefully checked the manuscript structure to ensure the definitions are properly presented before subsequent discussion.

18. Fig. 5&6 can be merged.

Re:

We agree that Figs. 5 and 6 could technically be merged to reduce page usage. However, according to the Copernicus manuscript preparation guidelines: “Figures and tables as well as their captions must be inserted in the main text near the location of the first mention (not appended to the end of the manuscript).” Because Figures 5 and 6 are associated with slightly different scientific interpretations, merging them would substantially increase figure complexity and reduce readability within the current manuscript structure. Therefore, we prefer to retain them as separate figures.

19. Line 372, where is Fig. 4a?

Re:

We thank the reviewer for identifying this mistake. “Fig. 4a” has been corrected to “Fig. 3a” in Line 388.

20. Physical interpretation is required for Fig. 6. For example, the moisture rich layer – rainfall intensity relations could be helpful.

Re:

We thank the reviewer for this valuable suggestion. Additional physical interpretation and discussion regarding the relationship between moisture-rich layers and rainfall intensity have been incorporated into the revised Section 3.3 (Lines 460 – 489), read as:

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.

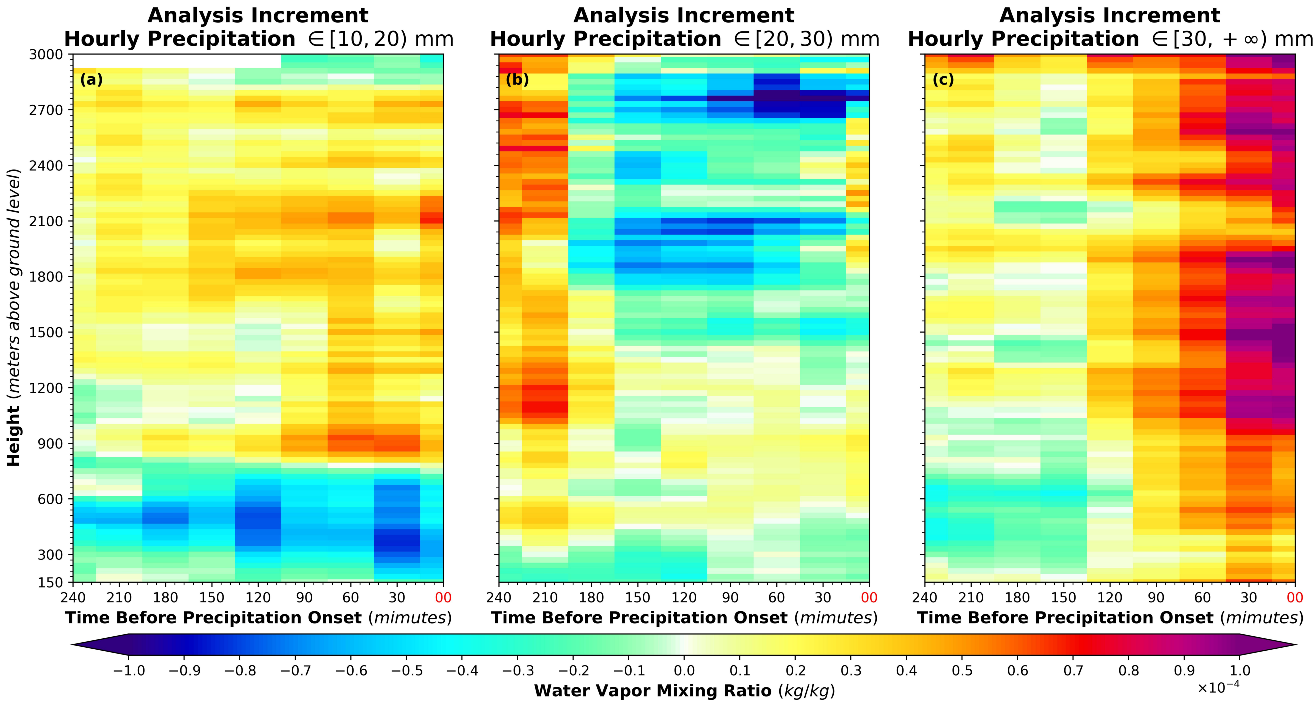

Figure 11: Temporal–vertical evolution of the case-averaged analysis increments in the TCKF1D-Var retrieved water vapor mass mixing ratio profiles relative to the ERA5 prior before the onset of nocturnal heavy precipitation for three hourly accumulated precipitation categories: (a) 10–20 mm, (b) 20–30 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.

21. It seems the assimilation approach only improves the accuracy by less than ~5%. Am I understanding correctly?

Re:

Yes, the reviewer’s understanding is correct. The magnitude of the analysis increments and retrieval improvements obtained in this study is consistent with the findings reported in recent related studies by Laly et al. (2024, 2025), which also demonstrated comparable levels of moisture-profile improvement relative to ERA5-based thermodynamic structures.

References:

Laly, F. and Chazette, P.: Comparative analysis of ERA5 and Raman lidar-derived moisture profiles in the framework of the WaLiNeAs field campaigns, Q. J. Roy. Meteor. Soc., 151, e5044, https://doi.org/10.1002/qj.5044, 2025.

Laly, F., Chazette, P., Totems, J., Lagarrigue, J., Forges, L., and Flamant, C.: Water vapor Raman lidar observations from multiple sites in the framework of WaLiNeAs, Earth Syst. Sci. Data, 16, 5579 – 5602, https://doi.org/10.5194/essd-16-5579-2024, 2024.

22. Section 3.3 provides two cases for case analysis. Firstly, these two cases are two extremes. Can you also provide one case from the middle category? Secondly, please add lines in these figures to show the precipitation time. Thirdly, the writing is somewhat redundant, please rephrase this section carefully. Line 425, actually, it is not that clear in Fig. 9a&b. It seems the approach developed in this study is less impactful for heavy rainfall compared to numerical products with good quality. Maybe an experiment using forecasts rather than reanalysis could lead to better results. Lastly, the analysis of these two cases lacks a physical perspective, especially for moisture evolution. Simply analyze the incremental pattern is insufficient, a physical based analysis, such as the linkage between moisture evolution and boundary layer processes, is necessary. BTW, radiosonde observations could also be used as priors. Comparisons using different priors will strongly benefit the paper.

Re:

We thank the reviewer for this valuable comment. We have addressed the concerns as follows:

a. Firstly, these two cases are two extremes. Can you also provide one case from the middle category?

We appreciate this helpful suggestion. In the revised manuscript, an additional median-like precipitation case has been incorporated into the refined Section 3.3 as Figure 10, aiming to provide a more representative demonstration between the two previously presented extreme cases.

b. Secondly, please add lines in these figures to show the precipitation time.

The precipitation onset time has now been highlighted in red on the x-axis tick labels in Figs. 8–11 to improve the readability and facilitate identification of the precipitation occurrence time.

c. Thirdly, the writing is somewhat redundant, please rephrase this section carefully.

We thank the reviewer for pointing this out. Section 3.3 has been substantially refined and reorganized to reduce redundancy and improve the overall clarity and readability of the discussion. The revised text is provided at the end of this response.

d. Line 425, actually, it is not that clear in Fig. 9a&b.

We agree with the reviewer. The corresponding statement has been revised.

e. **It seems the approach developed in this study is less impactful for heavy rainfall compared to numerical products with good quality. Maybe an experiment using forecasts rather than reanalysis could lead to better results.**

We sincerely appreciate this insightful suggestion. In fact, a similar single-station case-study framework focusing on data assimilation and numerical prediction applications has already been completed and published (Zhang et al., 2026). Building upon that work, additional DA–NWP experiments using the datasets generated in the present study are currently underway. We agree that employing forecast fields rather than reanalysis products as priors may further enhance the potential impact of the proposed approach in heavy precipitation forecasting scenarios. However, such investigations extend beyond the primary scope of the present manuscript. The objective of this study is to demonstrate the capability of the TCKF1D-Var framework, constrained by Mie–Raman lidar observations and reanalysis data, to retrieve boundary-layer water vapor profiles during non-radiosonde periods with radiosonde-comparable accuracy. Nevertheless, the reviewer's suggestion is highly valuable, and related DA–NWP applications will be explored and reported in future studies within journals whose aims and scope are more directly aligned with forecasting applications.

Reference: Zhang, Q., T. M. Chen, J. P. Guo, et al.: Enhancing boundary-layer forecast skill through KF1D-Var assimilation of Raman lidar thermodynamic profiles. J. Meteor. Res., 40(3), 1–17, https://doi.org/10.1007/s13351-026-5222-6, 2026.

f. **Lastly, the analysis of these two cases lacks a physical perspective, especially for moisture evolution. Simply analyze the incremental pattern is insufficient, a physical based analysis, such as the linkage between moisture evolution and boundary layer processes, is necessary.**

We thank the reviewer for this important suggestion. In response, we have substantially strengthened the physical interpretation in the refined Section 3.3. Specifically, composite analyses of the TCKF1D-Var retrieved water vapor mass mixing ratio profile analysis increments relative to ERA5 have been added for different hourly accumulated precipitation categories (10 − 20 mm, 20 − 30 mm, and ⩾ 30 mm). These additional analyses help provide a more physically meaningful interpretation of the moisture evolution characteristics associated with different precipitation intensities and their potential linkage to boundary-layer thermodynamic processes.

g. **BTW, radiosonde observations could also be used as priors. Comparisons using different priors will strongly benefit the paper.**

We highly appreciate this valuable suggestion. Whether ground-based remote sensing vertical observations can provide additional information content beyond that contained in conventional radiosonde observations is indeed an important and worthwhile research direction. We are very interested in pursuing this topic in future work. However, the primary scope of the present study is to demonstrate the capability of the TCKF1D-Var framework, constrained by Mie − Raman lidar observations and reanalysis data, to retrieve boundary-layer water vapor profiles during non-radiosonde periods, with the aim of providing boundary-layer thermodynamic profiles with radiosonde-comparable accuracy when radiosonde observations are unavailable. Nevertheless, the reviewer’ s proposed direction is scientifically meaningful, and comparative experiments using different prior datasets, including radiosonde observations, will be investigated in our future studies.

The refined Section 3.3 now reads as follows:

Although the statistical results presented in Section 3.2 reveal clear temporal and vertical variability in the analysis increments prior to nocturnal heavy precipitation, representative case studies are still necessary to determine whether these characteristics can also be identified in individual events. Therefore, three representative nocturnal heavy precipitation cases were selected for detailed analysis, corresponding to the maximum (Figure 8), minimum (Figure 9), and median-like (Figure 10) hourly accumulated precipitation intensities. The TCKF1D-Var retrieved water vapor mass mixing ratio profiles were compared with the ERA5 prior profiles to further evaluate the performance of the proposed method under different precipitation intensity conditions.

The maximum hourly rainfall case occurred at station 59293 at 16:00 UTC on 31 July 2025, with an hourly accumulated precipitation amount of 73.0 mm. Comparison of the TCKF1D-Var retrieved water vapor mass mixing ratio profiles at 30 min temporal resolution (Figure 8a) with the ERA5 prior profiles (Figure 8b) reveals pronounced analysis increments, particularly within the 0–1500 meters layer during the two hours preceding precipitation onset. Relative to ERA5, the TCKF1D-Var retrievals provide a more detailed depiction of upward moisture transport below 750 meters and enhanced temporal variability within the 750–1500 meters layer prior to precipitation. The evolution of the *Innovation* (Figure 8c) and reconstructed observations (Figure 8d) further supports these features. As precipitation onset approaches, both the magnitude and vertical variability of the reconstructed observations increase substantially, exhibiting temporal–vertical structures consistent with those shown in Figures 8a and 8b. This agreement indicates that the reconstructed observations derived from the MRL Raman channel measurements within the Kalman filtering framework are sensitive to the evolution of atmospheric moisture structures within the 0–3000 meters layer prior to nocturnal heavy precipitation. In addition, the consistency between the Innovation patterns and the corresponding moisture structures further supports the reliability of the observation operator used in this study.

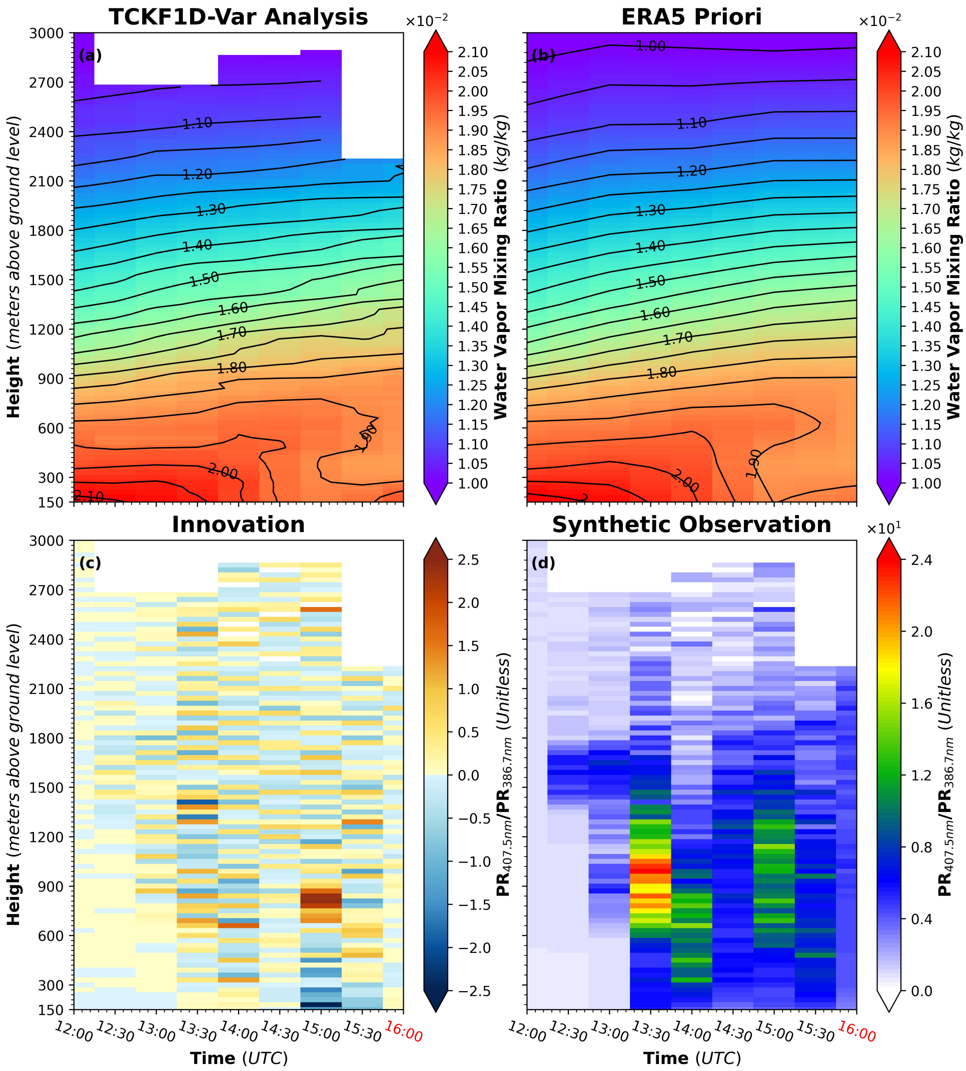

Figure 8: Time–height cross sections of (a) TCKF1D-Var retrieved water vapor mixing ratio at 30 minutes temporal resolution, (b) ERA5 prior water vapor mixing ratio, (c) Innovation, and (d) synthetic observations derived from the MRL Raman channel measurements, for the nighttime heavy precipitation case with maximum hourly rainfall intensity at station 59293 (16:00 UTC on 31 July 2025). The red-colored x-axis tick label (16:00 UTC) denotes the precipitation occurrence time.

The minimum hourly rainfall case (Figure 9) occurred at station 54218 at 19:00 UTC on 26 July 2025, with an hourly accumulated precipitation amount of 10.7 mm. Although identifiable analysis increments are also evident in this case, their vertical distribution differs markedly from that of the maximum rainfall event. The analysis increments are mainly concentrated above 1200 meters and are most pronounced within the 2100–3000 meters layer, consistent with the statistical characteristics identified in Section 3.2 (Figure 6a). Similar to the maximum rainfall case, the *Innovation* field exhibits temporal–vertical structures consistent with those shown in Figures 9a and 9b. Meanwhile, the reconstructed observations (Figure 9d) display progressively increasing magnitude and vertical variability as precipitation onset approaches. These results demonstrate that the TCKF1D-Var framework, together with the MRL Raman channel observations, is capable of capturing coherent moisture structure variations prior to precipitation under different rainfall intensity conditions.

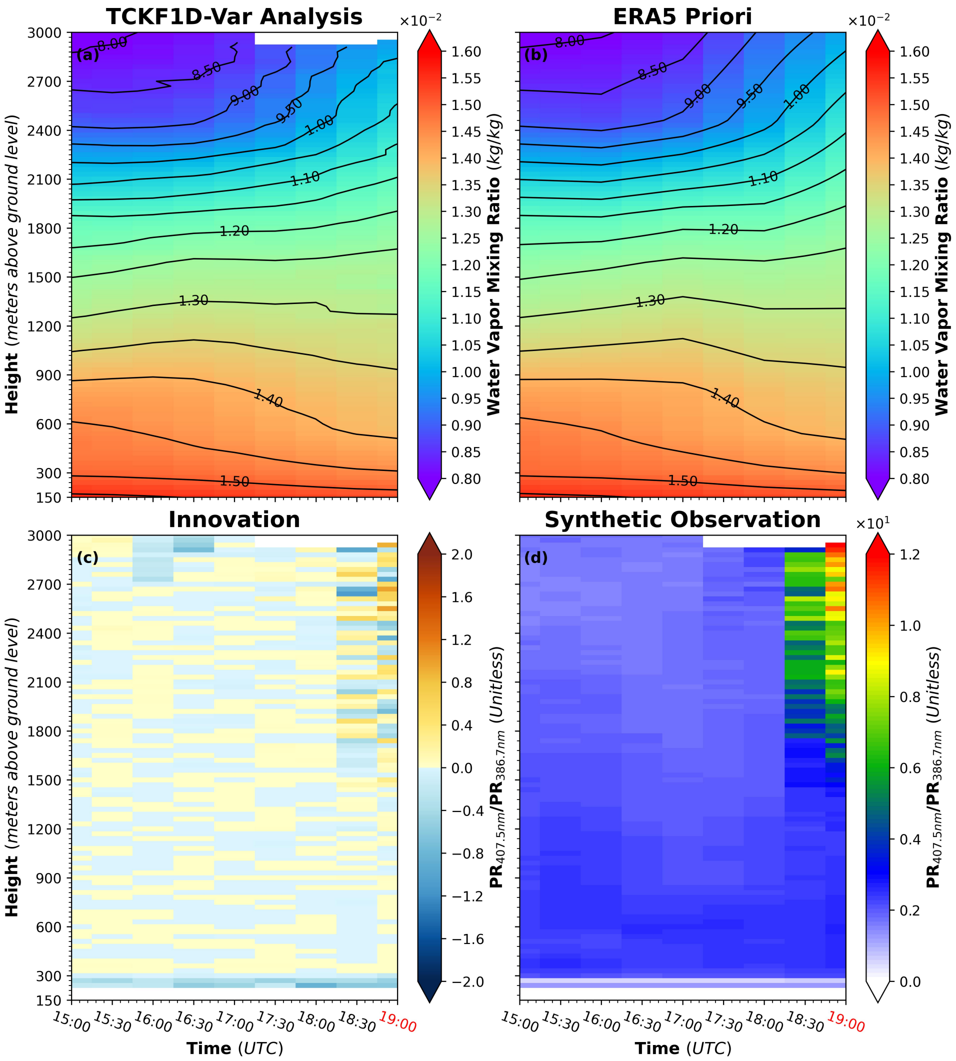

Figure 9: Time–height cross sections of (a) TCKF1D-Var retrieved water vapor mixing ratio at 30 minutes temporal resolution, (b) ERA5 prior water vapor mixing ratio, (c) Innovation, and (d) synthetic observations derived from the MRL Raman channel measurements, for the nighttime heavy precipitation case with minimum hourly rainfall intensity at station 54218 (19:00 UTC on 26 July 2025). The red-colored x-axis tick label (19:00 UTC) denotes the precipitation occurrence time.

The median-like hourly rainfall case (Figure 10) occurred at station 56492 at 16:00 UTC on 10 August 2025, with an hourly accumulated precipitation amount of 26.9 mm, which is closest to the median precipitation amount of 25.1 mm listed in Table 3. Comparison between the TCKF1D-Var retrieved profiles and the ERA5 prior profiles (Figures 10a and 10b) again reveals clear analysis increments, indicating substantial adjustments relative to the ERA5 prior state. However, the temporal and vertical characteristics of these increments differ from those identified in Figures 8 and 9. Within the 1200–3000 meters layer, clear departures from ERA5 become evident approximately two hours before precipitation onset, which is shorter than the lead time identified in the minimum rainfall case, where similar differences emerged nearly three hours prior to precipitation. In addition, the magnitude of the analysis increments within the 1200–3000 meteres layer is weaker than that observed in the minimum rainfall case. Below 1200 meters, the TCKF1D-Var retrieved profiles also begin to deviate from ERA5 approximately two hours before precipitation onset, consistent with the timing identified in the maximum rainfall case. Nevertheless, the main region of enhanced analysis increments is confined to the 600–1200 meters layer, which is narrower than the corresponding layer identified in the maximum rainfall case (150–1200 meters). The magnitude of the low-level analysis increments is also weaker than that in the maximum rainfall event.

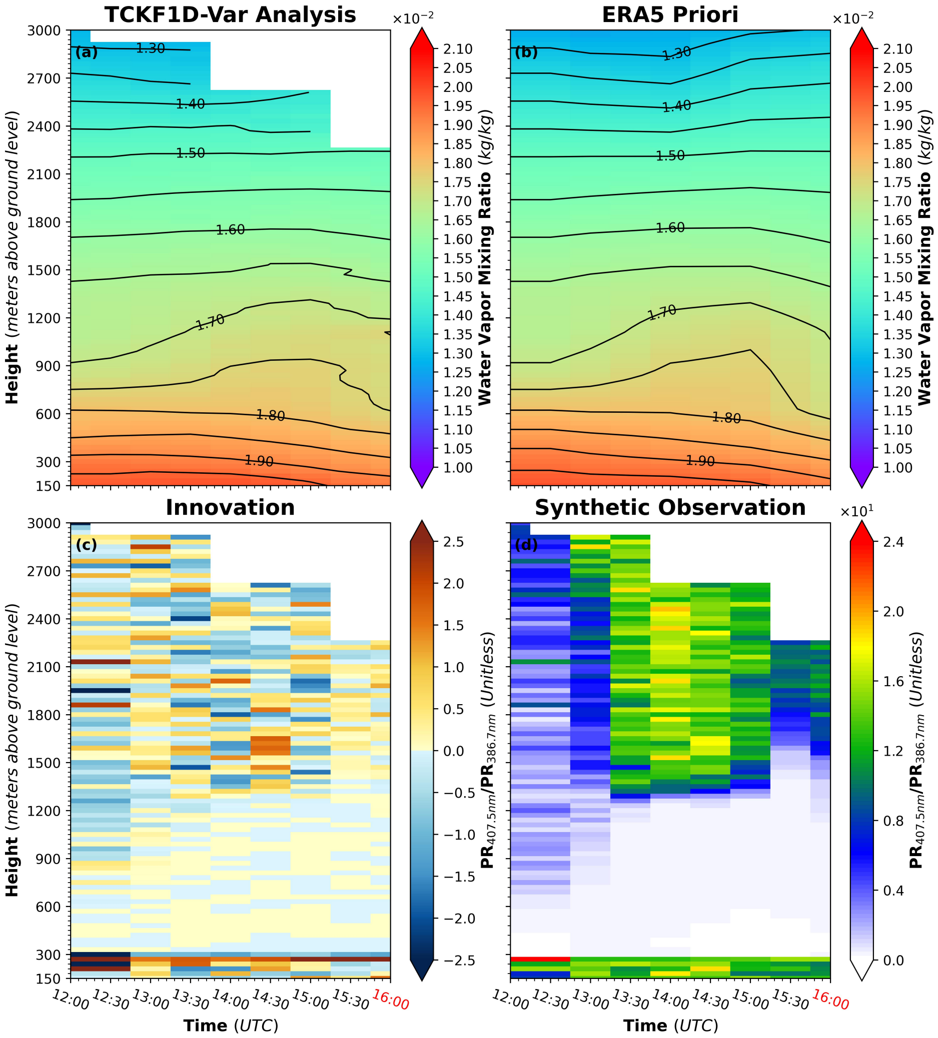

Figure 10: Time–height cross sections of (a) TCKF1D-Var retrieved water vapor mixing ratio at 30 minutes temporal resolution, (b) ERA5 prior water vapor mixing ratio, (c) Innovation, and (d) synthetic observations derived from the MRL Raman channel measurements, for the nighttime heavy precipitation case with minimum hourly rainfall intensity at station 56492 (16:00 UTC on 10 August 2025). The red-colored x-axis tick label (16:00 UTC) denotes the precipitation occurrence time.

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.

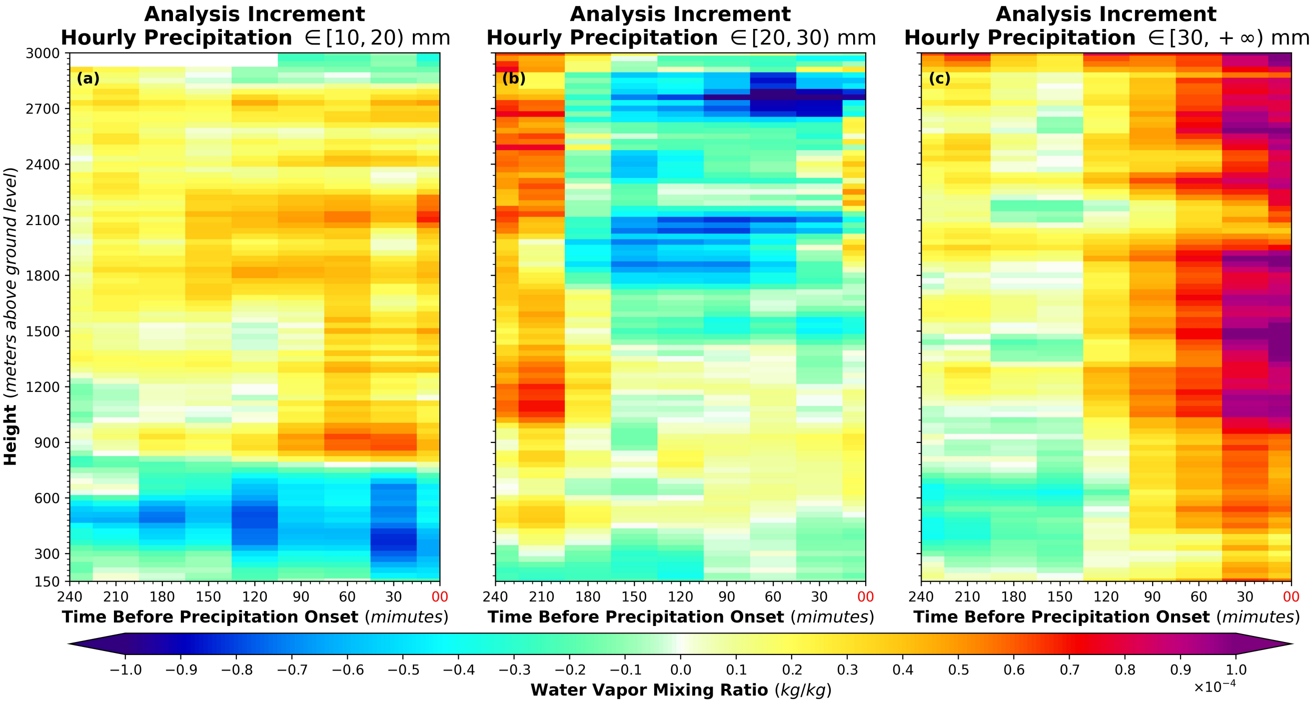

Figure 11: Temporal–vertical evolution of the case-averaged analysis increments in the TCKF1D-Var retrieved water vapor mass mixing ratio profiles relative to the ERA5 prior before the onset of nocturnal heavy precipitation for three hourly accumulated precipitation categories: (a) 10–20 mm, (b) 20–30 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.

23. Since Raman lidar has a blind area generally below 100 m, please add the bottom layer height in all the figures.

Re:

The blind range height (150 m) has now been added on the y-axis tick labels in Figs. 3–11 to improve the readablity.

24. Some grammar issues: "repetation" to "repetition", "mircophysics" to "microphysics".

Re:

We thank the reviewer for carefully checking the manuscript. The spelling error "repetation" in Line 59 has been corrected to "repetition", and "mircophysics" in Line 71 has been corrected to "microphysics". In addition, we have carefully proofread the revised manuscript to minimize other potential spelling and grammatical errors.

25. A table summarizing key retrieval settings (vertical resolution, time window, etc.) could benefit readers.

Re:

We thank the reviewer for this constructive suggestion. In the revised manuscript, the temporal and vertical resolutions of the TCKF1D-Var retrievals are reiterated in the "Summary and concluding remarks" section (Line 496) to further emphasize the key retrieval configurations. In addition, detailed product information associated with the TCKF1D-Var retrieval outputs has been archived in the Zenodo repository. Correspondingly, explanatory text has been added in the "Code and data availability" section (Lines 529 – 531), which now reads: "All TCKF1D-Var retrieval products are stored in NetCDF format. Detailed descriptions of the variables, dimensions, and metadata contained in the NetCDF files are provided in the accompanying product_introduction.pdf document included in the Zenodo repository."