Response to RC2

This study presents a ML-based multi-satellite fusion framework, successfully generating a high-resolution, all-weather TPW dataset for the Tibetan Plateau, which represents a significant contribution to the field. However, several methodological limitations and potential avenues for improvement warrant discussion.

Response: We sincerely thank Reviewer 2 for the valuable suggestions and thoughtful feedback. The manuscript has been thoroughly revised in response to the comments. Specific responses and the corresponding modifications are presented below.

Comment 1: A primary concern is the framework's heavy reliance on the Himawari-8/9 (H8/9) clear-sky TPW product as the foundational reference for both bias correction and spatial downscaling. While this strategy effectively mitigates inter-sensor biases, it inherently transfers the uncertainties and potential systematic errors of the H8/9 retrievals into the final fused product. Furthermore, the adaptive correction method for cloudy conditions, which extrapolates biases from clear-cloudy boundaries, may see its efficacy diminish in regions of extensive, persistent cloud cover where valid H8/9 reference pixels are distant. Future work could enhance robustness by incorporating cloud physical properties (e.g., from microwave sounders) or assimilating short-term numerical weather prediction fields to guide corrections in areas with minimal clear-sky information.

Response: Thank you for your constructive comments. In response to your concern, we provide our reply from two perspectives.

(1) Regarding the concern that using Himawari-8/9 (H8/9) clear-sky TPW as a reference might introduce additional systematic errors into the fused product:

H8/9 was selected as the reference field mainly because of its high accuracy, strong temporal continuity, high spatial resolution, and stable retrieval performance. In the revised manuscript (Lines 501–502), we added Table 2, which compares the validation results of H8 TPW, hourly-resampled multi-source microwave TPW (MW TPW), and the fused TPW against GNSS TPW data for 2017.

Table 2. Comparison of hourly TPW from H8 TPW, MW TPW, and fused TPW against GNSS observations in 2017.

Weather conditions	Data type	R	Bias (mm)	RMSE (mm)	RRMSE (%)	N
Clear sky	H8 TPW	0.95	0.38	1.94	27.24	143670
	MW TPW	0.89	-1.82	3.79	54.37	42367
Cloudy	MW TPW	0.88	-4.31	6.44	55.44	46545
	Fused TPW	0.95	-2.78	4.92	42.32	142063

As shown in Tab. 2, under clear-sky conditions, MW TPW has an RMSE of 3.79 mm, while H8 TPW shows a much smaller value of 1.94 mm. Under cloudy conditions, MW TPW has an RMSE of 6.44 mm, whereas the fused TPW improves to 4.92 mm, representing a 23.6 % reduction in error. This demonstrates that using the high-accuracy H8 TPW effectively reduces uncertainty in the fused data under cloudy conditions.

In addition, the multi-source microwave observations have a native temporal sampling of 1–3 hours and a coarse spatial resolution of 0.25°, while H8/9 provides continuous hourly observations with a 2 km resolution—the only dataset covering the entire Tibetan Plateau at such scales. Therefore, H8 supplies high-resolution, stable water-vapor information that the microwave data alone cannot provide. In the fusion framework, microwave data serve as a complementary source to fill the cloudy gaps of H8/9, whereas H8/9 acts as the primary reference for ensuring spatial and temporal consistency. Hence, H8/9 is not an additional error source but rather the most reliable and stable foundation for constraining multi-sensor consistency and enhancing the overall resolution of the fused TPW product.

(2) Regarding the performance of the adaptive correction under persistent cloud cover:

We agree with the reviewer that in regions with long-lasting and extensive cloud systems, the adaptive correction may become less effective due to the lack of sufficient clear-sky pixels, which can increase local uncertainty. Future improvements will focus on incorporating cloud physical parameters and short-term numerical weather prediction fields to further enhance correction accuracy under such conditions.

To clarify this point, we have added a new paragraph in the Discussion section (Lines 670–694) describing the current applicability of the algorithm and its potential extensions, as follows:

“5.2 Limitations and future improvements of the fusion algorithm

Although the proposed fusion algorithm successfully reconstructs continuous all-weather TPW fields with high temporal and spatial resolution over the Tibetan Plateau, several limitations remain to be addressed.

First, in the western part of the Tibetan Plateau, the original satellite observations show extensive data gaps because of the limited geostationary coverage and the sparse overpasses of microwave sensors. As a result, the available information for spatiotemporal interpolation is relatively insufficient, which may lead to reduced reconstruction accuracy in these regions. Future work will incorporate additional satellite observations—such as data from Fengyun-4A/B (FY-4A/B) and other geostationary missions—to improve the spatial and temporal coverage of the input datasets, thereby enhancing the quality of reconstructed TPW fields in regions with limited observations.

Second, in regions with persistent and extensive cloud cover, the adaptive correction may experience reduced effectiveness due to the scarcity of valid clear-sky reference pixels from Himawari-8/9 (H8/9). This can lead to locally increased uncertainties, particularly in areas with frequent deep convective systems such as the southern Plateau. Future improvements will focus on introducing additional physical constraints, including cloud microphysical parameters retrieved from infrared or microwave cloud products, and assimilating short-term numerical weather prediction (NWP) fields to enhance correction robustness and continuity under prolonged cloudy conditions.

Third, the current algorithm has been optimized for the Tibetan Plateau, focusing on high-resolution water vapor reconstruction to support regional atmospheric and hydrological studies. Future development can extend this framework toward a near-global scale by integrating multi-geostationary satellite observations to achieve hourly TPW coverage across most low- and mid-latitude regions. For high-latitude areas where geostationary satellites lack coverage, clear-sky TPW retrievals from polar-orbiting optical sensors such as MODIS and MERSI can be incorporated as complementary sources.

In the long term, developing a globally consistent, high-resolution, and purely satellite-based TPW fusion framework will establish a solid observational foundation for quantitative studies of atmospheric moisture transport, energy balance, and land–atmosphere coupling, and will further support the refinement of precipitation (Cui et al., 2025; Ji et al., 2025a), cloud property (Tana et al., 2023, 2025), and radiation estimation (Letu et al., 2023) algorithms across multiple spatial and temporal scales.”

Comment 2: It is not clear why PWV data from polar imagers such as MODIS or MERSI are not included in the analysis. These valuable data should provide a critical reference or add new information to the fused product.

Response: Thank you for your constructive comments. MODIS and MERSI provide two types of TPW products: thermal infrared (TIR) and near-infrared (NIR). Both are limited to clear-sky conditions and have significant constraints over the Tibetan Plateau. Specifically, taking MODIS as an example, it provides only two effective overpasses per day (one daytime and one nighttime). The TIR product can be retrieved both day and night but has a coarse spatial resolution (~5 km) and lower accuracy over complex terrain. The NIR product offers higher spatial resolution (~1 km) but is available only under daytime clear-sky conditions and is strongly affected by high surface albedo and frequent cloud cover over the Plateau, resulting in limited valid samples.

In contrast, the H8/9 TPW product provides continuous full-disk coverage every 10 minutes with a spatial resolution of about 2 km, offering stable, high-frequency, and high-accuracy water-vapor observations that serve as a reliable reference for multi-source fusion.

We conducted an hourly validation using GNSS TPW data in 2017 to compare the accuracy of the H8/9, MODIS-NIR, and MODIS-TIR TPW products. The results are summarized below:

Table. Validation of MODIS-NIR, MODIS-TIR, and Himawari-8 TPW against GNSS observations in 2017.

Product	R	Bias (mm)	RMSE (mm)	RRMSE (%)	N
NIR	0.91	0.86	3.05	43.57	2508

TIR	0.80	-2.35	4.61	63.11	6501
H8	0.95	0.38	1.94	27.24	143670

The time-matching window was set to ±15 minutes, and the spatial matching radius to 5 km. Among the three datasets, H8/9 shows the highest correlation with GNSS observations at 0.95, followed by MODIS NIR at 0.91 and MODIS TIR at 0.80. For bias, H8/9 exhibits the smallest deviation of 0.38 mm, MODIS NIR shows a slightly larger positive bias of 0.86 mm, and MODIS TIR presents a clear negative bias of −2.35 mm. In terms of overall accuracy, H8/9 again performs best with an RMSE of 1.94 mm and an RRMSE of 27.24%, whereas MODIS NIR and MODIS TIR show larger errors of 3.05 mm (43.57%) and 4.61 mm (63.11%), respectively. Considering that MODIS and MERSI neither provide additional temporal observations nor achieve higher validation accuracy compared with H8/9, incorporating these datasets into the fusion framework may not produce a positive influence on the final results. Therefore, these datasets were not incorporated into the current fusion framework.

Nevertheless, MODIS offers valuable high-resolution NIR observations over polar regions where H8/9 coverage is unavailable. As noted in the revised manuscript, future work will explore integrating MODIS or MERSI TPW observations into a global fusion framework. To address this point, the following text has been added to the Discussion section (Lines 685–689) of the revised manuscript:

"Third, the current algorithm has been optimized for the Tibetan Plateau, focusing on high-resolution water vapor reconstruction to support regional atmospheric and hydrological studies. Future development can extend this framework toward a near-global scale by integrating multi-geostationary satellite observations to achieve hourly TPW coverage across most low- and mid-latitude regions. For high-latitude areas where geostationary satellites lack coverage, clear-sky TPW retrievals from polar-orbiting optical sensors such as MODIS and MERSI can be incorporated as complementary sources."

Comment 3: Regarding validation, while the use of 44 GNSS stations is valuable, their sparse and uneven distribution, particularly over western and northern TP, limits the ability to comprehensively assess the product's accuracy across all topographic and meteorological regimes. The validation might not fully capture errors in the most data-scarce regions. Supplementing the evaluation with data from intensive field campaigns (for example, Scientific Expedition on the Tibetan Plateau), additional independent satellite retrievals, or a cross-validation study during periods with varied cloud cover would strengthen the confidence in the product's performance.

Response: Thank you for this valuable suggestion. In the revised manuscript, we have supplemented the validation by adding three new observational datasets — Integrated Global Radiosonde Archive (IGRA) TPW, and two types of TPW data from scientific expeditions over the Tibetan Plateau: (1) microwave radiometer (MWR) TPW over the Tibetan Plateau, and (2) GNSS TPW from the central Himalayas — and included their corresponding validation analyses.

To clearly describe these datasets, two new subsections have been added to the Data section of the revised manuscript (Lines 269–283), as follows:

"**2.2.4 IGRA radiosonde TPW data**

The Integrated Global Radiosonde Archive (IGRA) provides vertical profiles of temperature, humidity, and pressure at multiple levels. In this study, the TPW derived from IGRA observations in 2022 was used to independently validate the fused TPW dataset. The IGRA data were obtained from the National Climatic Data Center (Durre et al., 2006).

2.2.5 Scientific expedition ground-based TPW observations

Two types of ground-based observations from the scientific expedition were employed to further evaluate the fused TPW data:

(1) Microwave radiometer (MWR) observations: Continuous tropospheric observations (0–10 km) were obtained from the MWR network deployed across the Plateau during 2021–2022 (Chen & Ma, 2022; Chen et al., 2024). The instruments provide profiles of temperature and humidity at 58- or 83-layer vertical resolutions, from which TPW is derived. Observation sites include MAWORS, NADOR, Mangai, Naqu, Changdu, Leshan, QOMS, SETS, and Kabu.

(2) GNSS TPW observations in the central Himalayas: A five-station north–south GNSS chain was established along the Yadong–Lhasa fault zone (XYDX, DNLG, SMDX, JZLZ,

and LKZZ), providing high-accuracy (±0.1 mm) TPW retrievals from 2015 to 2019 (Wang et al., 2019; Yang, 2023). These data were used to validate the fused TPW performance in steep terrain regions of the central Himalayas.”

All three datasets were used for independent validation of the fused TPW product at the hourly scale.

Furthermore, the validation results from these newly added datasets were incorporated into a new subsection “**4.1.3 Additional validation using radiosonde and scientific expedition data**” (Lines 539–566) of the revised manuscript. The added text reads as follows:

“**4.1.3 Additional validation using radiosonde and scientific expedition data**

To further evaluate the performance of the fused TPW dataset, additional validations were conducted using (1) IGRA radiosonde TPW data from 2022, (2) microwave radiometer (MWR) observations obtained from the scientific expedition over the Tibetan Plateau in 2022, and (3) GNSS TPW observations from the central Himalayas in 2017. Table.x shows the metrics comparisons between the fused TPW, ERA5, and MIMIC-TPW2 datasets.

Table 3. Validation of the fused TPW, ERA5 TPW, and MIMIC-TPW2 products using independent observations from IGRA, ground-based MWR, and GNSS over the central Himalayas.

Observation Type	Data Type	R	Bias (mm)	RMSE (mm)	RRMSE (%)	N
IGRA (2022)	Fused TPW	0.96	0.08	2.15	27.66	5059
	ERA5 TPW	0.98	−0.34	1.55	19.93	5059
	MIMIC-TPW2	0.89	−0.38	3.26	41.93	5059
MWR (2022)	Fused TPW	0.86	−3.63	6.34	68.06	19280
	ERA5 TPW	0.92	−4.35	6.21	66.63	19280
	MIMIC-TPW2	0.84	−4.69	7.16	76.88	19280
GNSS (2017,	Fused TPW	0.92	−1.83	3.37	23.05	16623
	ERA5 TPW	0.91	−3.28	4.63	31.71	16623

Central Himalayas)	MIMIC-TPW2	0.86	−3.77	4.96	33.98	16623

For the IGRA validation, ERA5 exhibits the highest correlation of 0.98, followed by the fused TPW at 0.96 and MIMIC-TPW2 at 0.89. In terms of accuracy, ERA5 also achieves the smallest RMSE of 1.55 mm and the lowest RRMSE of 19.93 %, while the fused TPW shows slightly larger values of 2.15 mm and 27.66 %, and MIMIC-TPW2 shows the largest error of 3.26 mm and 41.93 %. The higher accuracy of ERA5 in this comparison may be partly attributed to its assimilation of radiosonde observations from the Global Telecommunication System (GTS) network, which includes the IGRA stations (Durre et al., 2006; Hersbach et al., 2020). The biases are 0.08 mm for the fused TPW, −0.34 mm for ERA5, and −0.38 mm for MIMIC-TPW2, indicating that the fused product has the smallest absolute bias among the three datasets.

For the MWR validation, the correlation coefficients are 0.86 for the fused TPW, 0.92 for ERA5, and 0.84 for MIMIC-TPW2. The RMSEs are 6.21 mm, 6.34 mm, and 7.16 mm for ERA5, the fused TPW, and MIMIC-TPW2, respectively, with corresponding relative RMSEs of 66.63 %, 68.06 %, and 76.88 %. All three datasets show a clear dry bias, −4.35 mm for ERA5, −3.63 mm for the fused TPW, and −4.69 mm for MIMIC-TPW2.

For the GNSS observations in the central Himalayas, the fused TPW shows a correlation of 0.92, higher than ERA5 at 0.91 and MIMIC-TPW2 at 0.86. Its RMSE (3.37 mm) and relative RMSE (23.05 %) are the smallest among the three datasets, compared with 4.63 mm (31.71 %) for ERA5 and 4.96 mm (33.98 %) for MIMIC-TPW2, indicating that the fused product achieves the highest accuracy in this region. The biases are consistently dry across all datasets, with the fused TPW showing the smallest magnitude at −1.83 mm, compared with −3.28 mm for ERA5 and −3.77 mm for MIMIC-TPW2.

According to these validation results, the accuracy is generally higher when evaluated using IGRA data, but becomes lower when using the scientific expedition data such as MWR and GNSS from the central Himalayas. Compared with global public datasets like IGRA, these expedition observations are located in more remote regions of the Plateau and are crucial for analyzing and validating water vapor transport across the TP. However, all datasets still show relatively large errors in such areas, and further improvements in retrieval accuracy are needed for complex and data-sparse regions.

Reference：

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Chen, X., Liu, Y., Ma, Y., Ma, W., Xu, X., Cheng, X., and Wang, B.: TP-PROFILE monitoring the thermodynamical structure of the troposphere over the Third Pole, Advances in Atmospheric Sciences, https://doi.org/10.1007/s00376-023-3199-y, 2024.

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