Response Letter

Ms. Ref. No.: egusphere-2026-1745
Title: High-frequency monitoring of SO_2 plumes from moderate-scale volcanic eruptions using a synergy of GEO and LEO satellites: A case study of the 2024 Kanlaon eruption
Atmospheric Chemistry and Physics

Our Response:

We thank the Editor and the two expert reviewers for their constructive comments, which have materially strengthened the rigor and presentation of the manuscript. We have made major and careful modifications to the original manuscript according to all the comments and suggestions from the reviewers.

The major changes include:

(1) Systematically expanded the uncertainty characterization of the GIIRS SO_2 retrieval. We added comprehensive sensitivity analyses in the main text (Section 4.2) and the Supplementary Materials to quantitatively evaluate the impacts of surface temperature variations, water vapor profile changes, and volcanic ash masking effects on retrieval performance. Detailed forward modeling of volcanic ash was also included in the supplement.

(2) Refined the theoretical details of the retrieval algorithm and model configurations. We restructured and expanded upon the specific details of the retrieval process: detailing the radiative transfer model (e.g., HITRAN database, and spectral resolution); clarifying the construction of the error covariance matrix (S_ε) and its representativeness of realistic environmental interferences; demonstrating the relationship between the spectral shape features of the Jacobian matrix (K) and varying SO_2 column densities through sensitivity tests; and clarifying the specific operational procedures for constraining the GIIRS SO_2 layer height using synergistic LEO satellite observations.

(3) Evaluated the operational detection threshold based on real observation scenarios. Building upon the theoretical detection limit, we incorporated a statistical evaluation of real SO_2-free background radiance pixels. The resulting empirical detection threshold (~4–6 DU at 10–15 km altitudes) inherently internalizes the impacts of realistic environmental interferences such as clouds and water vapor.

(4) Comprehensively revised inaccurate or absolute statements throughout the manuscript to enhance objectivity and rigor. We strictly reviewed the qualitative descriptions across the entire manuscript and corrected claims that lacked sufficient evidence. For example, we revised the inappropriate statements regarding the "global applicability" of the framework throughout the text, and discussed the physical limitations and application prerequisites when migrating this method to other environmental conditions.

Item-by-item responses to the specific comments are provided below. Modifications to the original manuscript are indicated by yellow highlights in the revised manuscript.

Response to Reviewer 1

General comments from reviewer 1:

This study integrates SO_2 plume height and column density retrieval from several GEO and LEO satellites to exhibit a case study of the 2024 Kanlaon eruption. The main innovation of this study is the weak v1 absorption band is leveraged to estimate SO_2 column density for FY-4B/GIIRS. The large differences between satellite retrievals and model simulations demonstrate the significance of the synergy of GEO and LEO satellites. Some comments should be addressed before the consideration of its publication.

Response to Reviewer 1's general comment

We sincerely thank the reviewer for taking the time to review our manuscript and for the positive overall assessment. We greatly appreciate your constructive comments, which are very helpful in improving the quality of this paper. We have carefully addressed all the specific comments and revised the manuscript accordingly. Please find our detailed point-by-point responses below.

Specific comments from reviewer 1:

R1-S1

1. Water vapor strongly absorbs radiation in both v1 and v3 band as shown Fig. 2. How does it affect the retrievals of SO_2 plume height and column density? Should water vapor profiles or water vapor column concentrations be determined prior to the retrieval of SO_2 plume height and column density?

Response:

We thank the reviewer for insightful comments. In our algorithmic framework, there is no need to separately determine or retrieve the water vapor profile prior to the SO_2 retrieval. Our retrieval algorithm can effectively overcome water vapor interference.

(1) Impact on SO_2 column density retrieval.

In our retrieval framework, water vapor fluctuations, along with other interfering factors such as cloud contamination and forward model errors, are encapsulated within the error covariance matrix ($\mathbf{S}_{\boldsymbol{\varepsilon}}$). The core of this retrieval method is based on fitting the SO_2 spectral shape. The spectral features described by the covariance matrix do not significantly affect the final SO_2 retrieval. Water vapor does not mask or distort the high-frequency SO_2 absorption spectral shape. In contrast, atmospheric effects that alter the SO_2 spectral signatures (such as clouds and volcanic ash located above the plume) weaken these spectral features and lead to underestimations in the retrieval **(Carboni et al., 2012)**.

Additionally, the presence of water vapor affects the true thermal contrast, which impacts the observation signal-to-noise ratio and the final retrieval. This impact is more pronounced for GIIRS due to its sole weak absorption band, whereas the impact on HIRAS is relatively minor. We have supplemented a sensitivity experiment in Section 4.2. By scaling the entire water vapor profile by factors ranging from 0.6 to 1.5 (in practice, we utilize ERA5 water vapor profiles, so the actual residual water vapor fluctuations are far less extreme), we observed that the impact of water vapor variations on the GIIRS SO_2 retrieval is limited. Taking an assumed 30 DU SO_2 plume as an example, when the water vapor scaling factor changes from 0.6 to 1.5, the relative error (underestimation) of the SO_2 retrieval only shifts from -28.0% to -30.7%, compared to -28.7% under the unperturbed condition (1.0x water vapor).

(2) Impact on SO_2 plume height estimation

The physical essence of the HRI method is to quantify the shape-matching degree between the observed spectra and the theoretical SO_2 spectral features. Interferences from unconstrained parameters in the atmosphere (including the natural presence and variation of water vapor) are already effectively accounted for in the background covariance matrix (**S**) constructed from real background observations. The presence of water vapor does not alter the relative shape of the SO_2 absorption cross-section across different altitudes. As long as this relative shape remains unchanged, HRI can accurately identify the altitude layer with the highest correlation (i.e., the peak-finding remains stable) **(Clarisse et al., 2026)**.

Updated Section 3.2:

"The resulting residual covariance matrix effectively encapsulates the combined influence of instrumental noise, forward model errors, observation geometries, and the variability of unresolved surface and atmospheric parameters (e.g., water vapor fluctuations, other interfering gases and clouds contamination) ..."

Updated Section 4.2:

"...At higher SO_2 concentrations, a negative deviation in actual water vapor yields better results by reducing lower-atmosphere continuum absorption and enhancing the true TC...";

"...Spectral signatures described by the covariance matrix (e.g., water vapor) have a limited impact on the SO_2 retrieval, primarily affecting the signal-to-noise ratio via TC... In contrast, coexisting volcanic ash can weaken the SO_2 spectral features... These results align with Carboni et al. (2012). Their study also included the impact of water clouds..."

Updated Fig. S2(b):

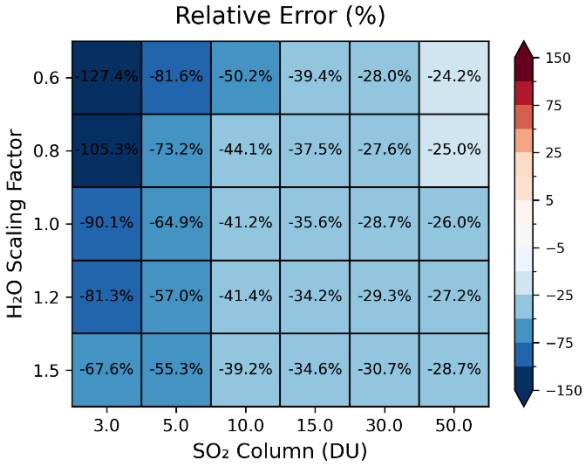


Fig. S2(b). Sensitivity analysis of the of FY-4B/GIIRS SO_2 retrievals under simulated environmental perturbations. Heatmaps show the retrieval relative errors induced by (b) scaled water vapor profiles (0.6 to 1.5).

R1-S2

2. Are the Jacobians in Sect. 3.1 sensitive to the variation in SO_2 columns. A constant SO_2 column density of 10 DU for each layer is used to while the true SO_2 column density could be quite different from the assumed constant. How does it affect the calculation HRI(h)? Will it lead to significant uncertainty of HRI(h), hence

the plume height estimation?

Response:

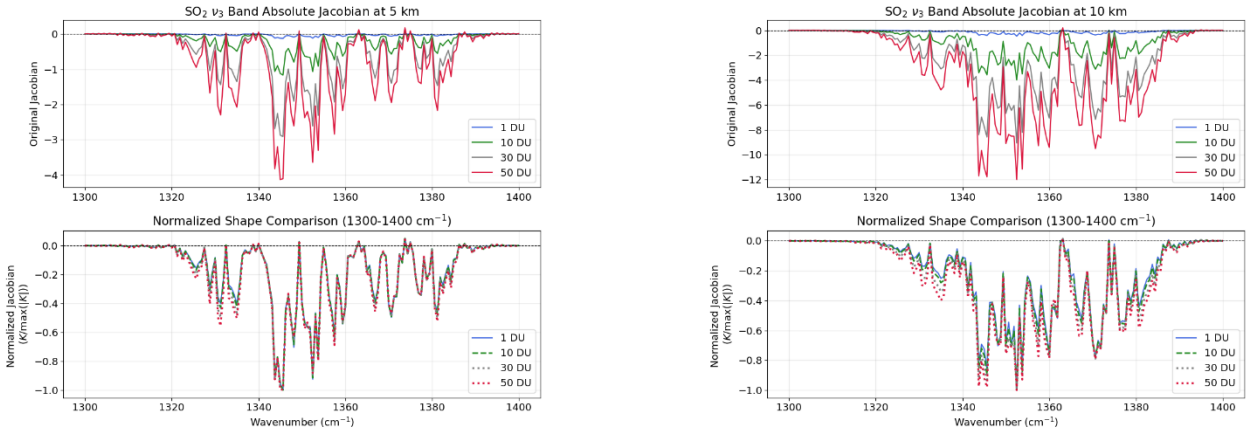
Yes, the absolute magnitudes of the Jacobians ($\mathbf{K}_{\boldsymbol{h}}$) are highly sensitive to variations in SO_2 column densities, but the normalized Jacobians (i.e., their relative spectral shapes) are insensitive to column variations. The core mechanism of the $\mathbf{HRI}(\boldsymbol{h})$ algorithm is to match the relative spectral shape between the observed spectra and the theoretical Jacobians within a covariance-weighted space, rather than fitting absolute radiances. Therefore, using a constant 10 DU assumption does not introduce significant uncertainty to the $\mathbf{HRI}(\boldsymbol{h})$ calculation and the subsequent plume height estimation.

To demonstrate this, we conducted a simulation experiment by extracting approximately 200 observation points from potential volcanic plume regions in the HIRAS data on June 2, 2024. We calculated and averaged the Jacobians for several different SO_2 column densities (1, 10, 30, and 50 DU) across various altitude layers. Here, we present the results for the 5, 10, 15, and 20 km altitudes. As shown in Figure R1, it can be seen that while the changes in the absolute magnitudes of the Jacobians are quite obvious, the relative spectral shapes remain highly consistent within the same altitude layer. Changes in true concentration primarily result in a near-linear scaling of the Jacobian matrix, and the normalized spectral shapes exhibit no significant distortion across different concentrations. Notably, for the most prevalent weak plume observations (~1 DU) in this Kanlaon eruption, the spectral shape matches the 10 DU assumption well.

Comparing the results across different altitudes reveals that shape perturbations caused by concentration variations are much smaller than the spectral shape variations induced by altitude differences. Therefore, as long as the shape variations caused by concentration do not obscure the altitude-dependent spectral features, using the pre-calculated 10 DU Jacobians can capture the maximum shape correlation between the observed spectra and the theoretical model, and estimate accurate layer height.

Updated Section 3.1:

"Although the absolute magnitudes of $\mathbf{K}_{\boldsymbol{h}}$ scale with varying SO_2 loadings, sensitivity tests (not shown) indicate that their normalized spectral shapes remain highly similar for different SO_2 columns at a given altitude. Using a fixed 10 DU proxy should not influence the height estimation."



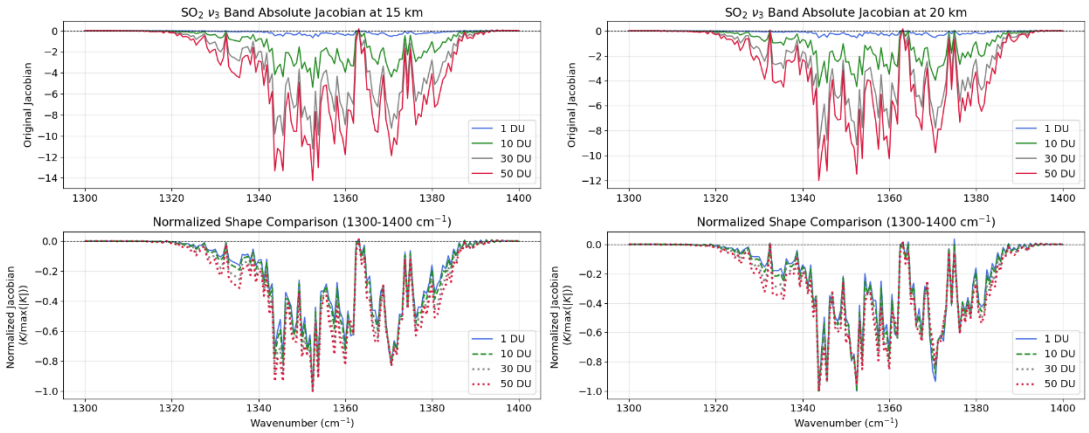


Fig. R1. Sensitivity of the absolute and normalized SO_2 *v*3-band Jacobians to varying column densities (1,10,30, 50 DU) at different altitudes (5, 10, 15, 20 km).

R1-S3

3. More explanations are needed for "Notably, the SO_2 layer height for the FY-4B/GIIRS observations is constrained using the retrieval results from the synergistic HIRAS and CrIS." How are the retrieve results applied to retrieve SO_2 layer height for the FY-4B/GIIRS observations?

Response:

GIIRS lacks the strong *v*3 band required for direct height retrieval, thus we utilized the synergistic LEO (HIRAS and CrIS) retrieval results. The specific procedure is as follows: for observations with concurrent LEO overpasses, the plume is divided into 1°–2° sub-regions, and the local representative heights (mean heights) from the LEO observations within each sub-region are assigned to the corresponding GIIRS pixels. For GIIRS observations lacking concurrent LEO overpasses, the heights are estimated via temporal interpolation along the plume transport trajectory. We have added these specific descriptions to the revised manuscript.

Updated Section 3.1:

"Notably, direct height retrieval from GIIRS spectra proved challenging due to its restricted spectral coverage, which only encompasses the weaker SO_2 *v*1 band. To overcome this, the layer height for GIIRS is constrained using synergistic LEO retrievals (HIRAS and CrIS). Specifically, the plume is divided into 1°–2° sub-regions, and the local averaged heights from concurrent LEO observations are assigned to the corresponding GIIRS pixels. For GIIRS observations lacking concurrent LEO overpasses, the heights are estimated via temporal interpolation along the plume trajectory."

R1-S4

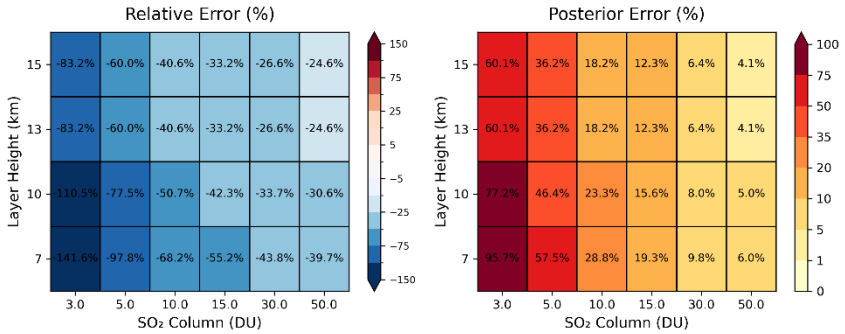
4. 3b and 3d are good. I suggest revising the vertical axis, with lower atmospheric levels at the bottom and upper levels at the top. This will avoid such misunderstanding when reader do not examine the figures carefully.

Response:

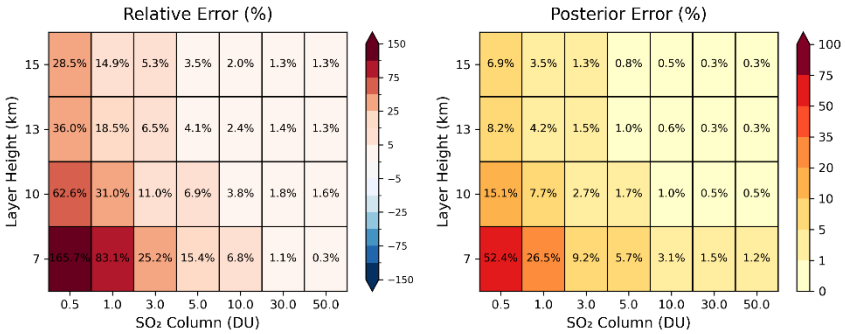
Changed as suggested.

Updated Fig. 3(b, d):

(b)



(d)



R1-S5

5. Line 50-59: All acronyms and abbreviations should be spelled out upon their first occurrence.

Response:

Changed as suggested.

Updated Section 1:

"The representative UV instruments include the Total Ozone Mapping Spectrometer (TOMS; e.g., Krueger, 1983), the Global Ozone Monitoring Experiment (GOME; e.g., Eisinger & Burrows, 1998), the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY; e.g., Lee et al., 2008), the Ozone Monitoring Instrument (OMI; e.g., Krotkov et al., 2006; Theys et al., 2015), the second-generation Global Ozone Monitoring Experiment (GOME-2; e.g., Rix et al., 2012), the Ozone Mapping and Profiler Suite (OMPS; e.g., Yang et al., 2013), and the TROPOspheric Monitoring Instrument (TROPOMI; e.g., Queißer et al., 2019; Theys et al., 2017). In the infrared, these sounders include the Moderate Resolution Imaging Spectroradiometer (MODIS; e.g., Corradini et al., 2009), the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER; e.g., Urai, 2004), the Atmospheric Infrared Sounder (AIRS; e.g., Carn et al., 2005), the Tropospheric Emission Spectrometer (TES; e.g., Clerbaux et al., 2008), the Infrared Atmospheric Sounding Interferometer (IASI; e.g., Carboni et al., 2012; Clarisse et al., 2008; Walker et al., 2012), the Cross-track Infrared Sounder (CrIS; Hyman & Pavolonis, 2020), and the Hyperspectral Infrared

Atmospheric Sounder (HIRAS; Li et al., 2025; Zeng et al., 2025). Additionally, volcanic SO2 can also be retrieved from microwave band measurements, such as the Microwave Limb Sounder (MLS; e.g., Pumphrey et al., 2015).”

R1-S6

6. The subscript 2 in SO_2 is often missing in many places.

Response:

We thank the reviewer for pointing this out. We have carefully checked the entire manuscript and corrected all instances where the subscript 2 in was missing.

References:

Carboni, E., Grainger, R., Walker, J., Dudhia, A., and Siddans, R.: A new scheme for sulphur dioxide retrieval from IASI measurements: Application to the Eyjafjallajökull eruption of April and May 2010, Atmospheric Chemistry and Physics, 12, 11417–11434, https://doi.org/10.5194/acp-12-11417-2012, 2012.

Clarisse, L., Franco, B., Fabris, L., Theys, N., Hadji-Lazaro, J., Hurtmans, D., Clerbaux, C., and Coheur, P.-F.: A 19-year record of atmospheric sulphur dioxide (SO2) derived from IASI measurements, Earth System Science Data, 18, 6667–6706, https://doi.org/10.5194/essd-18-6667-2026, 2026.