

## **Replies to referees:**

We thank both referees for their careful reading of our manuscript. The comments helped us improve the paper. We provide a point-by-point reply to the comments below.

February 5, 2025

## Replies to Reviewer 2

We thank the reviewer for the valuable comments and suggestions, which have improved the presentation of the paper.

★ **General Comments:** *In this work the Hyperspectral Infrared Atmospheric Sounder Type II (HIRAS-II), aboard the Fengyun 3E (FY-3E) satellite, is used to investigate the possibility to detect and retrieve the SO<sub>2</sub> emitted from volcanic eruptions. To do that, a methodology is described in order to select the most sensitive channels to SO<sub>2</sub> from the large number of hyperspectral channels recorded by the sensor. To minimize the influence of atmospheric water vapor and temperature to SO<sub>2</sub>, the procedure proposes to select SO<sub>2</sub>-sensitive channels that contain similar information on variations in atmospheric temperature and water vapor themselves. Finally, to test the procedure, the 29 April 2024 eruption of Mount Ruang in Indonesia has been considered.*

*Here, the possibility of using FY-3E - HIRAS-II for monitoring eruptive volcanic clouds is shown. This polar sensor is part of the set of polar and geostationary satellites working at different wavelengths used for the SO<sub>2</sub> monitoring, whose synergic use can significantly improve the monitoring of these natural phenomena. The proposed procedure is interesting but needs to be clarified in several parts. The considered test case shows that there is a qualitative analogy between the SO<sub>2</sub> cloud detected by HIRAS-II and that detected by TROPOMI on board Sentinel 5p.*

● **Response:** We sincerely appreciate your thorough review of our manuscript and your valuable feedback. Your comments have played a crucial role in enhancing the scientific rigor and completeness of our work. Additionally, we are grateful for your encouragement of our research efforts.

In the revised manuscript, we reselected the absorption regions for SO<sub>2</sub> and water vapor based on their spectral absorption characteristics. Additionally, we determined appropriate SO<sub>2</sub> perturbation thresholds to ensure that the results more

accurately represent the gas distribution features in real volcanic eruption scenarios. Based on this, we obtained the final channel selection results. Furthermore, we conducted additional experiments to validate the sensitivity of the SO<sub>2</sub> channels and their suitability for volcanic SO<sub>2</sub> detection. In response to the issues you raised, we have provided detailed replies in the manuscript, and these revisions and additions are fully reflected in the updated version.

★ *Specific comments:*

1. - *r23: in this work only qualitative information are extracted.*

- **Response:** Thank you for your comments. In the revision, we have removed the description of "quantitative" in the manuscript and revised the content as follows:

Using FY-3E/HIRAS-II measurements, the spatial distribution and qualitative information of volcanic SO<sub>2</sub> are easily observed. (**Revised manuscript line 25**)

2. - *r94: clarify the reference, Li et al., 1994 doesn't contain the equation inserted. Check also the sign of the different terms and define theta.*

- **Response:** Thank you for pointing out this problem. In the revised manuscript, we have corrected the cited references and thoroughly checked the parameter symbols in the equations to ensure their accuracy. The corrected reference is as follows:

- Li, J.: Temperature and water vapor weighting functions from radiative transfer equation with surface emissivity and solar reflectivity. Adv. Atmos. Sci., 11, 421-426, doi:10.1007/BF02658162, 1994.

Additionally, we have supplemented the definitions of  $T_{\text{sun}}$ ,  $T_s$  and  $\theta$  as they pertain to the equation for clarity, where  $T_{\text{sun}}$  is solar temperature,  $T_s$  is surface temperature and  $\theta$  is the zenith angle. (**Revised manuscript lines 97-100**)

3. - *r96: T is not present in the formula. You could explicit the dependence from T in the planck function (by written  $B_s(T_s)$  in the first term and  $B(T)$  into the integral.*

- **Response:** Thank you very much for your insightful comments. In the revised manuscript, we have explicitly indicated the dependence of T and B within the

Planck function in the equation (1) accompanied by appropriate annotations and explanations:

$$R = \varepsilon B_s(T_s)\tau_s - \int_0^{P_s} B(T)d\tau + (1 - \varepsilon) \int_0^{P_s} B(T)d\tau^* + 2.16 \times 10^{-5} \pi \cos \theta \times \rho_r B_r(T_{sun}) \times \tau_s^2$$

**(Revised manuscript line 97)**

4. - *r109-110: clarify if LBLRTM allows the possibility to insert a user defined atmospheric PTH profiles.*

- **Response:** Thank you for your suggestions. In the revised manuscript, we have clarified that the LBLRTM allows users to customize input profile files. Additionally, we have specified the content of the profiles used in our study. The details are as follows:

LBLRTM allows for the input of user-defined atmospheric profile files. In this study, the meteorological data input into LBLRTM consists of six standard atmospheric profiles: the US Standard Atmosphere, 1976, and profiles for mid-latitude summer, mid-latitude winter, subarctic summer and subarctic winter.

**(Revised manuscript line 113)**

5. - *r116 Paragraph 2.2: are the HIRAS-II data freely available? Where they can be downloaded? This information could be inserted in the text.*

- **Response:** Thank you for your valuable feedback. FY-3E/HIRAS-II data are freely available from the FENGYUN Satellite Data Service (<https://satellite.nsmc.org.cn/DataPortal/cn/home/index.html>). We have incorporated these contents into the revised manuscript. **(Revised manuscript line 133)**

6. - *r125-r127: what about the NEdT for the short-wave bands?*

- **Response:** Thank you for raising this question. Since our study did not utilize spectral channels in the shortwave band, we did not initially include relevant information on this band. However, based on your suggestion, we realized that adding the NEDT information for the shortwave band would enhance the overall

coherence of the manuscript and provide a more comprehensive description of the data. In the revised manuscript, we have incorporated this information as follows:

Based on the radiometric specifications for FY-3E/HIRAS-II, the noise equivalent target brightness temperature (BT) difference (NEdT) is specified within 0.2 – 0.4 K for the long-wave IR band, 0.2 – 0.3 K (at 280 K) for the mid-wave IR band and 0.8 – 2.4 K (at 280 K) for the short-wave IR band (Huang et al., 2023).  
(Revised manuscript line 131)

7. - *Table 1: as written in the paper "Its measurements span a continuous spectrum range of 648.75 to 2551.25 cm<sup>-1</sup> at a resolution of 0.625 cm<sup>-1</sup>". In the table seems that the different spectral intervals are not in continuity. For example: the Long spectral range ended at 1136 cm<sup>-1</sup> and the Mid spectral range start at 1210 cm cm<sup>-1</sup> (lack of 74 cm<sup>-1</sup>). Why some channels have been not considered?*

- **Response:** Thank you for your questions. We sincerely thank the reviewer for their careful observation regarding the spectral range distribution in our study. After reviewing the relevant literature and official technical documentation of FY-3E/HIRAS-II, we found that the HIRAS L1 data are released in two spectral resolution modes: Full Resolution (FR) and Design Resolution (DR) (Li et al., 2022). In the originally submitted manuscript, we mistakenly presented the spectral range distribution of different resolution modes as the Full Resolution data, and we apologize for this oversight. In fact, our study utilizes the Full Resolution data from FY-3E/HIRAS-II, with a spectral resolution of 0.625 cm<sup>-1</sup>. In the revised manuscript, we have corrected this error and updated the relevant tables and data descriptions to ensure the accuracy and consistency of our results. (Revised manuscript Table 1)

Table 1 Spectral parameters of FY-3E/HIRAS-II channels (Xie et al., 2023)

IR Wave Band	Spectral Range (cm <sup>-1</sup> )	No. of Channels	Spectral Resolution (cm <sup>-1</sup> )
Long	648.75 – 1169.375	834	0.625

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	(15.41 – 8.55 $\mu\text{m}$ )		
Mid	1167.5 – 1921.25 (8.56 – 5.20 $\mu\text{m}$ )	1207	0.625
Short	1919.375 – 2551.25 (5.21 – 3.92 $\mu\text{m}$ )	1012	0.625

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8. - *r139: citation not present in the bibliography.*

- **Response:** Thank you for your suggestion. In the revised manuscript, we have added the relevant reference to the reference list. The added reference is as follows:
  - Corradino, C., Jouve, P., La Spina, A., Del Negro, C.: Monitoring Earth's atmosphere with Sentinel-5 TROPOMI and Artificial Intelligence: Quantifying volcanic SO<sub>2</sub> emissions. *Remote Sensing of Environment*, 315, 114463, doi:<https://doi.org/10.1016/j.rse.2024.114463>, 2024.

**(Revised manuscript line 509)**

9. - *r141-r142: Please insert the references:*

- *Theys, N.; De Smedt, I.; Yu, H.; Danckaert, T.; Van Gent, J.; Hörmann, C.; Wagner, T.; Hedelt, P.; Bauer, H.; Romahn, F.; et al. Sulfur dioxide retrievals from TROPOMI onboard Sentinel-5 Precursor: Algorithm theoretical basis. *Atmos. Meas. Tech.* 2017, 10, 119–153.*

- *Theys, N.; Hedelt, P.; De Smedt, I.; Lerot, C.; Yu, H.; Vlietinck, J.; Pedergnana, M.; Arellano, S.; Galle, B.; Fernandez, D.; et al. Global monitoring of volcanic SO<sub>2</sub> degassing with unprecedented resolution from TROPOMI onboard Sentinel-5 Precursor. *Sci. Rep.* 2019, 9, 1–10.*

- **Response:** Thank you for your suggestions. We have carefully reviewed the two references and found that the content provides significant insights and valuable guidance for our work. We have included these references in the revised manuscript, as detailed below:

Daily or sub-daily revisits of specific sites are achievable, given TROPOMI's 108° cross-orbit field of view and its ability to capture data across multiple orbits

(Theys et al., 2017). Since 2019, Sentinel-5P's spatial resolution has been enhanced to 3.5 km × 5.5 km. TROPOMI measures data across four spectral regions (ultraviolet, visible, near-infrared, and shortwave infrared) and is adept at monitoring SO<sub>2</sub> and a range of other gases (Theys et al., 2019). **(Revised manuscript line 147-149)**

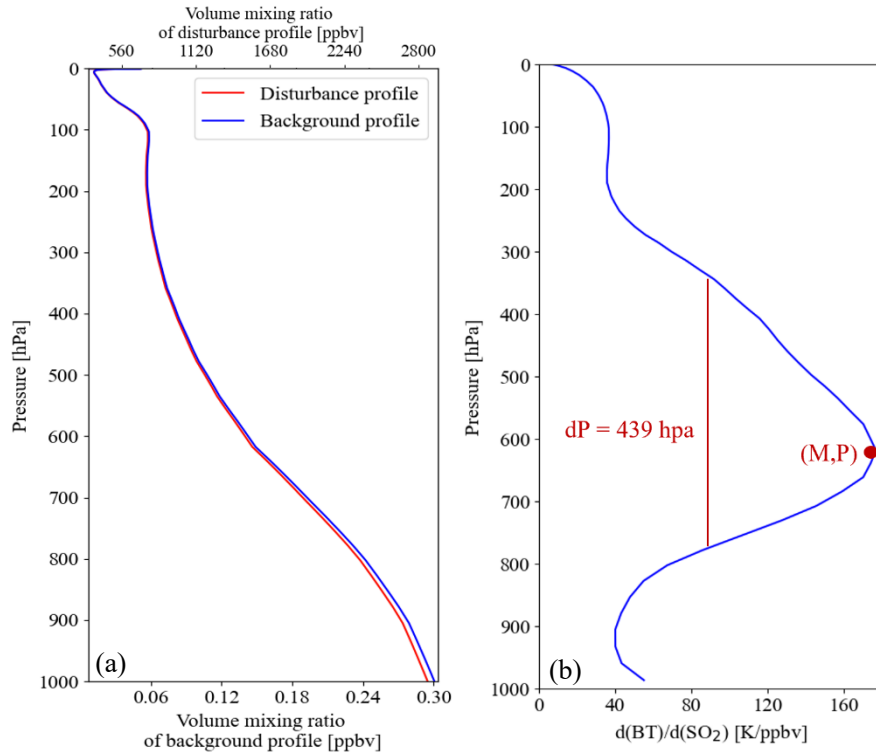
10. - *Figure 3: enlarge the x and y number labels (as in plot (b)). You should use ppbv instead of ppmv (in both plots). Here the brightness temperature is indicated as  $T_b$ , while in the text with BT, please standardize.*

- **Response:** Thank you for pointing out this problem. In the revised manuscript, we have redrawn Figure 3. Based on your suggestion, we have made the following modifications in the new image:

**First**, we have increased the font size of the x and y labels and ensured consistency between the two subfigures.

**Second**, we have changed the sulfur dioxide concentration to ppbv and applied this modification throughout the study.

**Finally**, we have updated the brightness temperature symbol in the image to BT, ensuring consistency with the rest of the manuscript. **(Revised manuscript Sec. 3.2 Figure 3)**



**Figure 3: Representation of the maximum half-width and peak value of the SO<sub>2</sub> Jacobian function for the US Standard Atmosphere, 1976: (a) SO<sub>2</sub> profile, (b) 1163.125 cm<sup>-1</sup> channel.**

11. - r217-r219: *explain better why the similarity in the Jacobians in the different spectral ranges is important to minimize the influence of water vapour and temperature to SO<sub>2</sub>.*

- **Response:** Thank you for raising this important question. As suggested, we have enhanced the explanation in the revised manuscript regarding the significance of Jacobian similarity across spectral ranges in mitigating water vapor (H<sub>2</sub>O) and temperature (T) interference on SO<sub>2</sub> retrievals. The rationale can be summarized in two key aspects:

**(1) Radiance sensitivity to the atmospheric information**

CO<sub>2</sub> absorption channels primarily reflect the information of atmospheric temperature profiles (Li et al., 2022), water vapor channels contain both temperature and water vapor information, while SO<sub>2</sub> channels contain information of temperature, water vapor and SO<sub>2</sub>. To separate temperature from water vapor in water vapor absorption channel radiances, CO<sub>2</sub> channels play an important role through providing temperature information. If a water vapor absorption channel



and a CO<sub>2</sub> absorption channel have similar temperature Jacobian, they have also similar temperature sensitivity, and thus that CO<sub>2</sub> channel is helpful for separating the temperature from water vapor in the water vapor channel radiance. Same for a SO<sub>2</sub> channel, if a water vapor channel has similar temperature Jacobian and water vapor Jacobian, then the water vapor channel is helpful for separating temperature and water vapor from SO<sub>2</sub> in that SO<sub>2</sub> channel radiance.

## **(2) Jacobian Consistency Protocol**

Through inter-channel Jacobian matching, we ensure that the variations in water vapor Jacobian matrix and temperature Jacobian matrix within the water vapor absorption region are consistent with those in the SO<sub>2</sub> channels.

Thus, when subtracting the brightness temperature of the SO<sub>2</sub> channel from that of the water vapor channel, the influence of water vapor, atmospheric temperature, and surface radiation shared by both channels can be effectively.

**This methodology effectively decouples SO<sub>2</sub> signals from confounding atmospheric states, with full implementation details provided in the revised manuscript (Lines 229-244).**

12. - *Figure 4: This scheme it is not so clear to me:*

*is it correct that the spectral range selected for the water vapor absorption region is the same as for the SO<sub>2</sub> absorption region? In this case the water vapor Jacobian matrix (computed for a specific wavenumber, by varying the water vapour content) should be the same. The water vapor selection is in this case carried out by considering the maximum  $M$  and  $dP$ ? In the scheme seems that only the cross-comparison between the water vapour Jacobians lead to the selection of the SO<sub>2</sub> channels. Is it correct? Moreover, it is not also clear to me why only the 1155-1430 interval is considered for the SO<sub>2</sub> Jacobian computation. SO<sub>2</sub> presents two wide absorption bands around 1163 and 1370  $\text{cm}^{-1}$ , and until 1100  $\text{cm}^{-1}$  the SO<sub>2</sub> absorption is still meaningful. Why the whole 1100-1430  $\text{cm}^{-1}$  spectral range it is not considered? I'm surprise to see that no one channels around 1163  $\text{cm}^{-1}$  is selected. This SO<sub>2</sub> absorption is inside of one of the TIR atmospheric window and*

*generally used for the SO<sub>2</sub> tropospheric retrievals.*

- **Response:** Thank you very much for your valuable suggestions and comments. We will address your comments from two aspects:

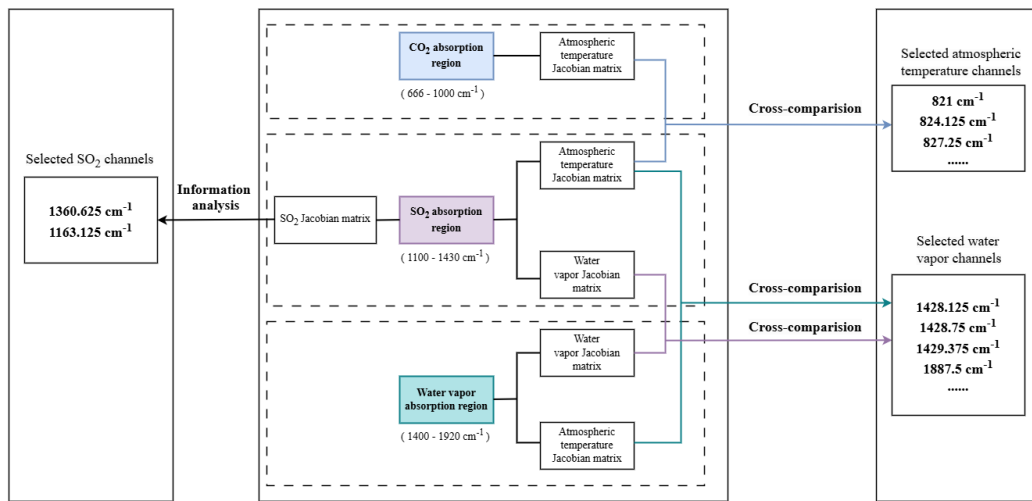
(1) We recognized that the previously selected water vapor absorption region had certain limitations. Therefore, based on the spectral absorption characteristics of water vapor, we reselected the water vapor absorption region within the range of 1400 – 1920 cm<sup>-1</sup> (7.14 – 5.20 μm) and re-screened the water vapor channels within this new absorption region (Rodimova, 2018). Additionally, we redrew Figure 4 to more clearly illustrate the channel selection process.

Specifically, the SO<sub>2</sub> channels were selected based on the Jacobian information analysis method. The atmospheric temperature channels were determined by comparing the temperature Jacobians in the CO<sub>2</sub> absorption region with those of the selected SO<sub>2</sub> channels. The selection of water vapor channels was conducted in two steps: first, by comparing the temperature Jacobians in the water vapor absorption region with those of the SO<sub>2</sub> channels; second, by comparing the water vapor Jacobians in the water vapor absorption region with those of the SO<sub>2</sub> channels. Ultimately, we identified suitable water vapor channels that have both similar temperature and water vapor Jacobians of SO<sub>2</sub> channels. Note that we identified SO<sub>2</sub> channels first, then found water vapor channels with similar Jacobians, those selected water vapor channels do not have SO<sub>2</sub> absorption, meaning there is no overlapping channel between selected water vapor channels and the SO<sub>2</sub> channels. The idea on selecting CO<sub>2</sub> and water vapor channels with similar T/q Jacobians of SO<sub>2</sub> channels is to separate temperature and water vapor from SO<sub>2</sub> in the SO<sub>2</sub> channels radiances.

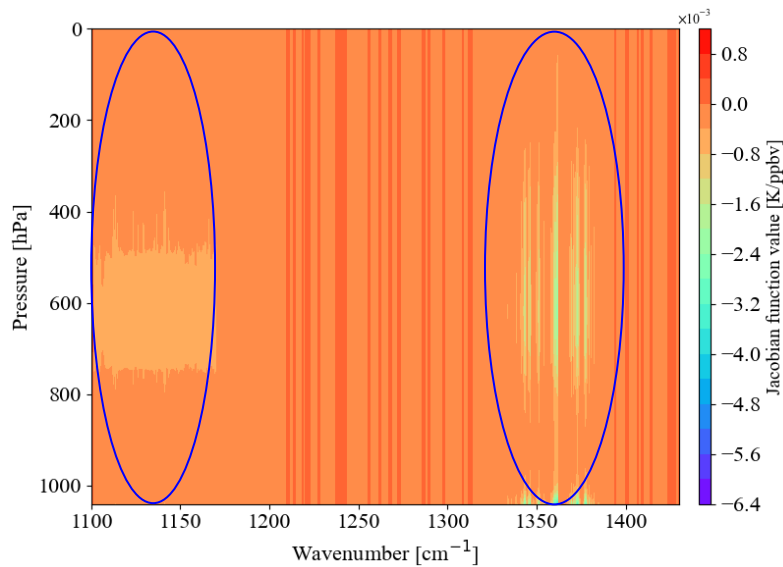
(2) We agree with the reviewer's comments regarding the selection of SO<sub>2</sub> channels and have revised our SO<sub>2</sub> channel selection accordingly. In the new scheme, we have expanded the SO<sub>2</sub> absorption region to 1100 – 1430 cm<sup>-1</sup>. Since the 1100 – 1170 cm<sup>-1</sup> spectral region is highly effective for detecting SO<sub>2</sub> plumes in the troposphere and is particularly valuable for monitoring volcanoes characterized by continuous passive degassing (Carboni et al., 2016), we have

reselected SO<sub>2</sub> channels within this range. Given that the chosen channels can effectively capture SO<sub>2</sub> across different atmospheric layers, we have carefully selected channels from both 1100 – 1170 and 1320 – 1370 cm<sup>-1</sup> bands to ensure comprehensive coverage.

In conclusion, we have incorporated the necessary revisions into the revised manuscript, and provided Figure 4 and Figure 5 below. **(Revised manuscript Sec. 3.2)**



**Figure 4: Schematic diagram of channel selection method.**



**Figure 5: Schematic diagram of the SO<sub>2</sub> Jacobian matrix with atmospheric profiles from the US Standard Atmosphere, 1976.**

13. - r226: the SO<sub>2</sub> perturbation is generated by varying a default profile of 5%. But,

*during volcanic emission, the SO<sub>2</sub> content is much higher and also confined at specific layers. How the SO<sub>2</sub> Jacobian computed can be considered representative of a real case?*

- **Response:** Thank you for pointing out this problem. After reviewing relevant literature, we found that the background atmospheric SO<sub>2</sub> concentration is typically ranges from 0.25 – 0.43 ppbv. During volcanic eruptions, however, SO<sub>2</sub> concentrations are significantly higher, ranging from approximately 500 – 1000 ppbv. Therefore, we increased the SO<sub>2</sub> perturbation magnitude to  $5 \times 10^4$  times the background SO<sub>2</sub> concentration in ppbv to ensure that our perturbation levels are representative of actual volcanic eruption scenarios.

Additionally, although SO<sub>2</sub> in real volcanic eruption events is generally concentrated in specific atmospheric layers, volcanic eruptions are typically rapid and prolonged. To ensure the completeness of our simulation results, we applied perturbations to all 99 atmospheric layers from 0 to 1040 hPa in our study. The modified content in the manuscript is as follows :

In situ measurements reported by Rose et al. (2004) indicate SO<sub>2</sub> concentrations of 500 – 1000 ppbv during an aircraft encounter with a 35-hour-old volcanic plume from the Icelandic Hekla eruption in February 2000, at a distance of approximately 1300 km from the source. In comparison, the concentration of SO<sub>2</sub> in the clean troposphere typically ranges from 0.25 – 0.43 ppbv (Casadevall et al., 1984). Given that SO<sub>2</sub> concentrations increase dramatically over a short period during volcanic eruptions, for SO<sub>2</sub>, we perturb the atmospheric profiles at different pressure levels using  $5 \times 10^4$  times gas content, to better represent the gas distribution characteristics in volcanic eruption scenarios. **(Revised manuscript line 251-256)**

14. - *r228-r231: except for the wavenumbers around 1360 cm<sup>-1</sup>, Figure 5 doesn't clearly emphasize where are placed the other wavenumbers significant. In any case the left orange oval (that should emphasize the higher jacobian variability) is placed around 1210 cm<sup>-1</sup> and not 1225 cm<sup>-1</sup>.*

- **Response:** Thank you for your valuable suggestions. We fully acknowledge the importance of channels within the 1100 – 1170  $\text{cm}^{-1}$  spectral range for  $\text{SO}_2$  monitoring. Although this range is located within the atmospheric window and the  $\text{SO}_2$  signal intensity is weaker compared to the 1320 – 1370  $\text{cm}^{-1}$  range, its significant advantage lies in its minimal susceptibility to water vapor interference. This characteristic makes the 1100 – 1170  $\text{cm}^{-1}$  range particularly valuable for monitoring  $\text{SO}_2$  in the middle and lower troposphere. In the revised manuscript, we have further emphasized the importance of the 1100 – 1170  $\text{cm}^{-1}$  range and selected specific channels within this range for  $\text{SO}_2$  monitoring, thereby enhancing the accuracy and reliability of  $\text{SO}_2$  detection in the middle and lower troposphere. The revised content in the manuscript is as follows:

The 1360  $\text{cm}^{-1}$  band exhibits the strongest  $\text{SO}_2$  signal among the available spectral bands. However, it is also a strong absorption region for atmospheric water vapor, which can introduce contamination in  $\text{SO}_2$  retrievals. This band demonstrates minimal sensitivity to radiative contributions from the surface and lower atmosphere, making it particularly effective for monitoring stratospheric  $\text{SO}_2$  plumes (Thomas & Watson, 2010). In contrast, the 1163  $\text{cm}^{-1}$  band falls within an atmospheric window region. While the presence of  $\text{SO}_2$  in this band leads to a certain degree of radiative attenuation, it remains well-suited for detecting  $\text{SO}_2$  plumes in the troposphere (Carboni et al., 2016). This characteristic makes it especially valuable for monitoring volcanic activity characterized by continuous passive degassing. By leveraging the complementary strengths of these bands, we select  $\text{SO}_2$ -sensitive channels with a central wavenumber around 1163 and 1360  $\text{cm}^{-1}$ . (**Revised manuscript line 259-268**)

15. - r306: *it is not clear which channels have been selected, please clarify.*

- **Response:** Thank you for your comments. After reassessing the selection of  $\text{SO}_2$  channels, we have ultimately identified two  $\text{SO}_2$  channels, 1163.125 and 1360.625  $\text{cm}^{-1}$ . Based on this, we have supplemented the sensitivity analysis of the 1163.125  $\text{cm}^{-1}$  channel with respect to the temperature difference between the surface and

near-surface air in our original study. In the revised manuscript, we have clearly specified the channels used for sensitivity analysis. Additionally, we have provided a detailed comparison and discussion of the results obtained from both the 1163.125 and 1360.625  $\text{cm}^{-1}$  channels. (**Revised manuscript Sec. 4.1**)

16. - r317: *why the 1165.125  $\text{cm}^{-1}$  channel has been considered? The Paragraph 3.2.1 ( $\text{SO}_2$  channel selection) indicates only the channels around 1360  $\text{cm}^{-1}$ .*

- **Response:** Thank you for your question. In previous research, we conducted a sensitivity analysis of  $\text{SO}_2$  plumes using the 1360.625  $\text{cm}^{-1}$  channel and observed significant signal saturation in this channel when  $\text{SO}_2$  plume concentrations exceeded 200 DU. Simultaneously, we noted that the 1160.125  $\text{cm}^{-1}$  channel also contains partial  $\text{SO}_2$  information. Based on this, we further analyzed the sensitivity of the 1163.125  $\text{cm}^{-1}$  channel to  $\text{SO}_2$  plumes. The results demonstrated that the 1160.125  $\text{cm}^{-1}$  channel effectively avoids the saturation issues encountered in the 1360.625  $\text{cm}^{-1}$  channel under high  $\text{SO}_2$  plume concentrations. Therefore, in the revised manuscript, we have selected both the 1163.125 and 1360.625  $\text{cm}^{-1}$  channels as the primary channels for  $\text{SO}_2$  monitoring. This approach enhances the completeness of  $\text{SO}_2$  channels selection, improving the accuracy and reliability of detection. (**Revised manuscript Sec. 3.2.1**)

## References:

- Carboni, E., Grainger, R.G., Mather, T.A., Pyle, D.M., Thomas, G.E., Siddans, R., et al.: The vertical distribution of volcanic SO<sub>2</sub> plumes measured by IASI. *Atmos. Chem. Phys.*, 16, 4343-4367, doi:10.5194/acp-16-4343-2016, 2016.
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- Rose, W.I., Gu, Y., Watson, I.M., Yu, T., Blut, G.J.S., Prata, A.J., et al.: The February–March 2000 Eruption of Hekla, Iceland from a Satellite Perspective, *Volcanism and the Earth's Atmosphere*, pp. 107-132, 2004.
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