An 18-year record of atmospheric sulphur dioxide (SO2) derived from IASI measurements

https://doi.org/10.5194/essd-2026-186

Response to Referee #1

The paper provides a thorough record of volcanic SO2 column abundances and plume altitudes from 2007 to 2025, utilizing data from the three IASI instruments aboard Metop platforms. The first section details enhancements to SO2 retrieval methods, including sensitivity and uncertainty analyses. Notably, the refined retrievals demonstrate increased sensitivity to low SO2 concentrations at plume edges and improved plume altitude estimates for large columns. The authors have ensured consistency across instruments and throughout the time series. Uncertainty is minimized for SO2 plumes above 8 km, but increases at lower altitudes, especially in conditions of elevated atmospheric water vapor, and clouds and ash presence. Comparisons with CALIOP and TROPOMI reveal that plume altitude retrievals are accurate within 1–2 km, except for the case of high stratospheric Hunga plum, where explicit height constraint was necessary (figure 8). Overall, there is reasonable agreement with TROPOMI SO2 column retrievals for volcanic plumes above 8 km. The latter part of the manuscript introduces the 18-year IASI dataset, emphasizing volcanic SO2 mass, altitude distribution, and comparisons with prior IR and UV SO2 mass retrievals. The presentation is clear, and the manuscript is ready for publication.

We would like to thank the Referee for the positive evaluation of this paper and for the comments that contributed to improving the manuscript. Please find in blue font here below our response to the comments and the changes made to the manuscript.

In addition to the changes listed below, we have extended the IASI SO_2 time series (columns and altitudes) to the end of July 2026. Figures 18-20 and Table 2 have been updated accordingly. The extended time series reveals no major SO_2 enhancements associated with volcanic eruptions in 2026, except for moderate SO_2 masses emitted by Kilauea in early 2026. As the dataset now spans 19 years (July 2007 – July 2026) rather than 18 years, we have updated the title accordingly, as well as the corresponding mentions of the dataset's temporal coverage throughout the manuscript. The IASI SO_2 dataset publicly available on the Aeris portal (https://iasi.aeris-data.fr) has been updated to include the SO_2 data for 2026.

Specific Comments:

Introduction: The introduction should acknowledge pioneering satellite UV volcanic SO2 retrievals from TOMS (Krueger, 1983; Krueger et al., 1995), as well as current operational satellite UV SO2 datasets from OMPS and OMI (Li et al., 2024; Li et al., 2020). Additionally, real-time satellite SO2 retrievals for aviation avoidance should be referenced (Krotkov et al., 2021).

We have revised the second paragraph of the Introduction to acknowledge these SO_2 retrievals and to include the suggested references. Please note that Li et al. (2024) was already cited in the Introduction as one of the long-term SO_2 datasets derived from OMPS. The relevant changes relative to the original text are shown in ***bold font*** below:

"*For several decades, global SO2 total column abundances (and more recently plume heights) have been routinely measured by nadir-viewing high-resolution spectrometers onboard satellites**, building on the pioneering ultraviolet (UV) volcanic SO2 detections by the Total Ozone Mapping Spectrometer (TOMS) (Krueger, 1983; Krueger et al., 1995).** The most commonly used long-term SO2 datasets are derived from UV measurements by OMI (Yang et al., 2007; Fioletov et al., 2013**; Li et al., 2020**), OMPS (Zhang et al., 2017; Li et al., 2024) and TROPOMI (Theys et al., 2022) and infrared (IR) measurements by AIRS (Prata and Bernardo, 2007; Carn et al., 2016) and IASI (Clarisse et al., 2012; Carboni et al., 2016). The satellite-derived SO2 datasets support a wide range of scientific and operational applications, including volcanological studies (e.g., Pardini et al., 2018; D'Aleo et al., 2019), early warning systems of volcanic unrest **and aviation hazard avoidance** (e.g., Surono et al., 2012; Brenot et al., 2021**; Krotkov et al., 2021**), investigations of volcanic plume dispersion and dynamics (e.g., Prata et al., 2017; Khaykin et al., 2022), …*"

Section 2: The HRI solution for SO2 plume height is non-unique and requires additional constraints, particularly for high-altitude plumes such as the Hunga eruption (see Figure 7b–d and Figure 8).

The altitude solution is unique below 23 km, and this is generally the altitude selected on a pixel-by-pixel basis. When the retrieved altitude exceeds 23 km, it is generally replaced by the median of neighboring altitudes, except when the associated HRI is very high, as already described in Sect. 2.1. The non-uniqueness only concerns some pixels associated with the 2022 Hunga Tonga eruption, where HRI(y, h) exhibits two competing local maxima, one below and one above roughly 23 km (Fig. 7b–d). In such cases, CALIOP measurements were useful in confirming the exceptionally high altitude of the plume (Sect. 2.3.6, Fig. 8). This is now explained at the end of Sect. 2.1 as follows:

*"… and since the vast majority of detected SO_2 is at altitudes below this, these altitudes are also replaced by the median of neighbouring altitudes. **For some pixels associated with the 2022 Hunga Tonga eruption, HRI(y, h) exhibits two competing local maxima, one below and one above roughly 23 km, making the altitude solution non-unique for these pixels (see Fig. 7). In such cases, the exceptionally high altitude of the plume was confirmed using CALIOP measurements (Sect. 2.3.6).**"*

Section 3.4: While the authors address interference from clouds and volcanic ash in SO2 column retrievals, they do not discuss potential interference from oxidized sulfate aerosols, which are always co-located with SO2. Volcanic sulfate aerosol optical depth and mass can also be simultaneously retrieved from IASI measurements. Interference from water vapor is noted as a significant issue for altitudes below 8 km in the tropics; it would be beneficial to discuss this further, particularly regarding hydrated Hunga aerosol and SO2 plumes.

Sulfate aerosols exhibit their strongest absorption/scattering features around 1100 cm^{-1}, while their optical effect within the 1320-1410 cm^{-1} spectral range used for the SO_2 retrieval is weak and spectrally flat. We therefore do not expect a large interference on the retrieved SO_2 columns. We have added a new subsection (Sect. 3.4.5; here below) to discuss that point. We also note that IASI-based sulfate aerosol retrievals (Karagulian et al., 2010; Sellitto et al., 2024) offer a promising avenue for jointly characterizing this co-located aerosol and potential interference in future work.

*"**3.4.5 Sulfate aerosols***

Volcanic SO_2 is progressively oxidized into sulfate aerosols, which are therefore, to some extent, co-located with the SO_2 plume, in particular for aged plumes. Unlike clouds and ash (Sect. 3.4.4), however, sulfate aerosols exhibit their strongest absorption/scattering features around 1100 cm^{-1}, while their optical effect within the 1320-1410 cm^{-1} spectral range used for the SO_2 retrieval is comparatively weak and spectrally flat. A large interference on the retrieved SO_2 columns is therefore not expected. Sulfate aerosol optical depth and mass can nonetheless also be retrieved from IASI radiances, simultaneously with SO_2 (Karagulian et al., 2010; Sellitto et al., 2024), offering a promising avenue for jointly characterizing this co-located aerosol and potential interference in future work."

Regarding water vapour, we now clarify that the sensitivity estimates in Sect. 3.4.1 are derived from a climatology of typical atmospheric conditions, in which water vapour is essentially absent at the high altitudes reached by most volcanic plumes. This is why such interference in our uncertainty budget is largely confined to altitudes below 8-10 km. This assumption is nonetheless violated for the 2022 Hunga Tonga eruption, which injected an unprecedented ~146 Tg of water vapour directly into the stratosphere, co-located with the SO_2 and sulfate aerosol plume at altitudes of 28-30 km (Legras et al., 2022; Millán et al., 2022). We have added a sentence to Sect. 3.4.1 (in ***bold font*** here below) noting this anomalous high-altitude hydration as a plausible, event-specific source of additional interference not captured by our standard sensitivity analysis.

"... winter, with its drier atmosphere, provides more favourable conditions for retrieving SO_2.

The sensitivity estimates above are derived from a climatology of typical atmospheric conditions, in which water vapour is essentially absent at the high altitudes reached by most volcanic plumes. This assumption is nonetheless violated for the 2022 Hunga Tonga eruption, which injected an unprecedented ~146 Tg of water vapour directly into the stratosphere, co-located with the SO_2 and sulfate aerosol plume at altitudes of 28-30 km (Legras et al., 2022; Millán et al., 2022). This anomalous high-altitude hydration is a plausible additional source of interference for this specific event, unaccounted for by the standard sensitivity analysis presented here.

Taken together, we conclude that for plumes above 8 km, a conservative estimate ..."

Conclusions: The statement, "the new IASI SO2 dataset is also suited for long-term analysis of anthropogenic SO2," is not substantiated, as anthropogenic SO2 cases are not presented in the manuscript. Figure 14 illustrates an instance where IASI did not detect a low-altitude Etna plume over North Africa that was observed by TROPOMI. It may be more accurate to state that UV-based and TIR-based IASI retrievals are complementary and could be combined to improve detection of weak degassing volcanic and anthropogenic SO2 sources.

We agree that this sentence, as originally worded, was not sufficiently supported by the results presented in the manuscript. We have revised it to reflect the complementarity between IASI and UV-based sensors such as TROPOMI for weak/low-altitude SO_2 sources, consistent with the comparison presented in Sect. 3.5 (Fig. 14), rather than claiming a standalone capability for anthropogenic SO_2 that is not demonstrated in this study:

"***Although not explored in this study, IASI and UV-based sensors such as TROPOMI, which is more sensitive to weak, low-altitude SO_2 sources (see Sect. 3.5), are complementary and could be combined in future work to improve the detection of weak degassing volcanic and anthropogenic SO_2 sources.***"

Technical Corrections:

- Line 255: Reference the new TROPOMI Hunga sulfate aerosol (which is co-located with SO2) height retrieval, which aligns with IASI and CALIOP measurements (Spurr et al., 2026).

We thank the Referee for pointing us to this recent study. We have added a sentence noting that the TROPOMI/OMPS-based height retrieval of the co-located sulfate aerosol layer by Spurr et al. (2026) is also in good agreement with IASI and CALIOP, providing independent support for the altitude structure of the Hunga plume reported in this section.

"*... the agreement for the layers at 19-25 km and 28-32 km is remarkable, and to our knowledge, has not been demonstrated by any other SO_2 layer altitude algorithm. For instance, for the CrIS retrievals presented in Sadeghi et al. (2025), the altitudes are mainly centred around 15 ± 2 km for observations between 16 and 21 January.* ***A recent TROPOMI/OMPS-based height retrieval of the co-located sulfate aerosol layer (Spurr et al., 2026) similarly aligns well with both IASI and CALIOP, providing independent, complementary support for the altitude structure reported here.***"

- Figures 13, 14, 15: Include total SO2 mass for quantitative comparison in panels a, b, and c.

We have regenerated Figs. 13-15 to include the total SO_2 mass in panels a–c, allowing a direct quantitative comparison alongside the visual comparison of the plume distributions.

- Figure 15b: Note that the eastern portion of TROPOMI data is missing.

The eastern portion of the Raikoke plume is indeed captured by TROPOMI, but in a separate overpass with a substantial time offset relative to the one shown in Fig. 15. Including it would make the plume appear artificially disconnected from the main structure displayed here. We have added a clarifying note to the figure caption:

"*Figure 15. Same as Fig. 13, but during the eruption of Raikoke in June 2019.* ***The eastern portion of the plume, captured by TROPOMI during a separate overpass, is not shown here, as the resulting time offset would make it appear disconnected from the plume displayed here.***"

- Figure 16: The dark background reduces visibility; switch to a white background similar to Figures 13–15.

We chose not to switch to a white background as suggested, as this would reduce the visibility of low SO_2 concentrations given the colormap used, which we wish to keep consistent with the other SO_2 column figures throughout the manuscript. The dark appearance of the original figure was primarily due to the display of all IASI pixel footprints, including those without SO_2 detection, which we included to convey IASI's spatial coverage. As this coverage is already well illustrated elsewhere in the manuscript, we have regenerated Fig. 16 without these no-detection footprints, resulting in a substantially brighter background while preserving the colormap.

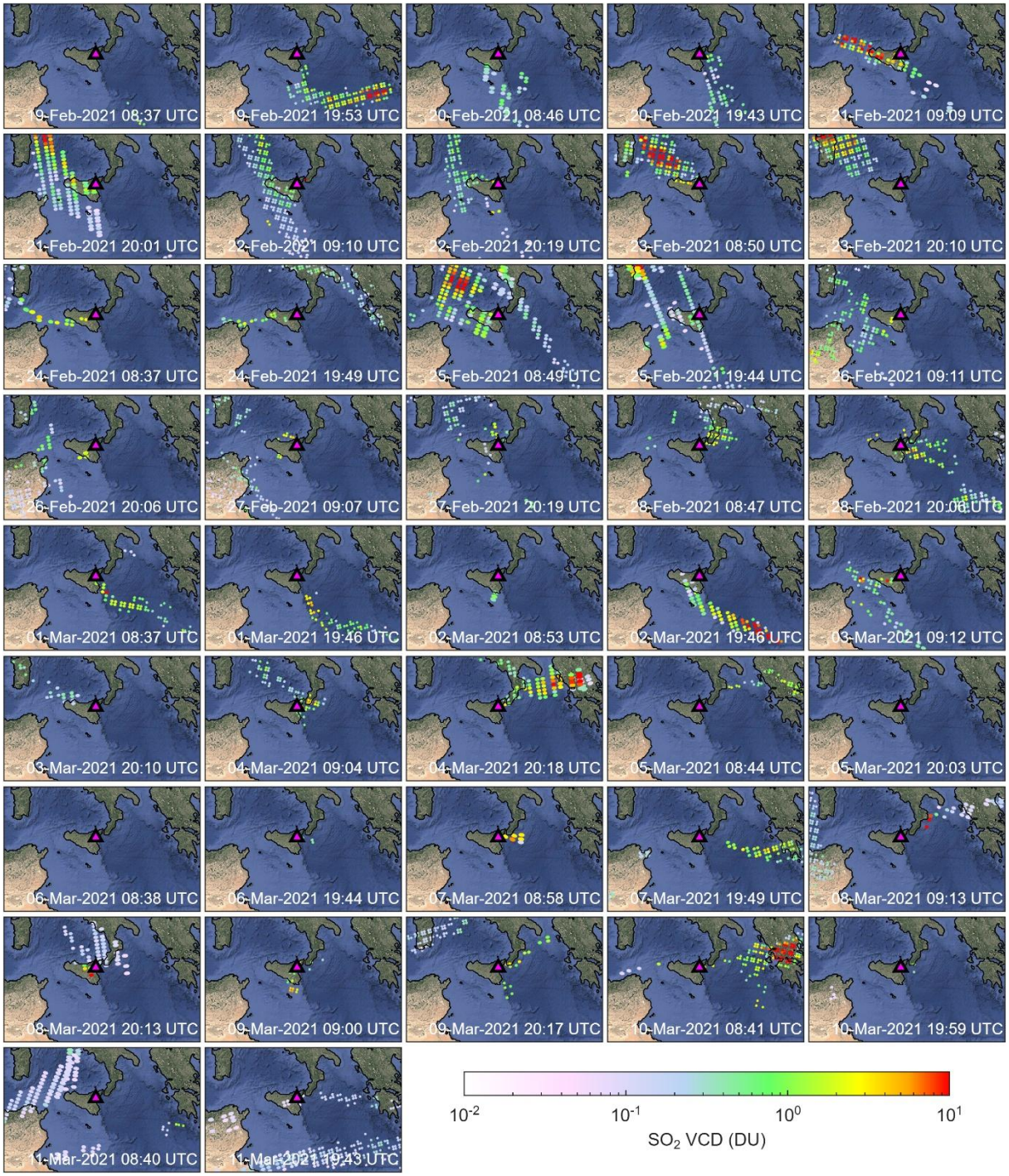

Figure 16. SO_2 VCD (in DU) retrieved from the twice-daily IASI/Metop-B measurements over Etna (triangle) during 21 consecutive days in March 2021. Each dot corresponds to the on-ground footprint of an individual IASI observation.

- Line 563: Replace "inter-" with "intratropical."

Done.

- Page 31, line 588: Indicate that Hunga long-range stratospheric SO2 clouds were located above 18–20 km.

We have added a sentence (in ***bold font*** here below) clarifying that point:

"*… IASI detected an initial injection exceeding 30 km, while subsequent, larger SO_2 masses were confined between 16 and 18 km, consistent with the regional tropopause height.* ***The more dilute SO_2 that was transported over long range and persisted in the following weeks was located slightly higher, between 18 and 20 km (Fig. 19).***"

- Line 604: Clarify that SO2 emissions from anthropogenic sources were primarily reduced due to the installation of desulfurization scrubbers. SO2 emissions remain high for Indian coal power plant and Russian Norilsk smelter in Siberia.

We have added this information to text as follows:

"*As discussed in Sect. 4.2, this results mostly from the substantial reductions in anthropogenic SO_2 emissions in China since the early 2010s****, primarily through the large-scale installation of desulfurization scrubbers at coal-fired power plants. Emissions remain comparatively high, however, for other major anthropogenic sources, such as coal-fired power plants in India and the Norilsk smelter in Siberia, Russia (Fioletov et al., 2023).***"

- Lines 690–694: Mention interference from water vapor for tropospheric and hydrated stratospheric eruptions, such as Hunga.

We have added a sentence to the Conclusions noting that water vapour is an additional source of interference.

"*… accounting explicitly for clouds and ash within the retrieval framework is an important avenue for future development.* ***Water vapour is another important source of interference, most notably for low-altitude tropospheric plumes in humid regions, but also, more unusually, for hydrated stratospheric plumes such as that of the 2022 Hunga Tonga eruption (Sect. 3.4).***"

- Lines 695–700: Indicate whether IASI-NG will offer higher spatial resolution or eliminate inter-orbital gaps.

IASI-NG retains a swath and pixel size similar to IASI, and therefore neither eliminates the inter-orbital coverage gaps at low latitudes nor improves spatial resolution. We amended the text to state this explicitly. Regarding spectral resolution and radiometric noise, preliminary assessments indicate that IASI-NG's noise in the v3 SO2 band is in fact higher than IASI's, unlike in most other spectral regions. The improved spectral resolution may compensate for this, but as this would require dedicated work beyond the scope of the present paper, we have chosen not to speculate on the net effect on SO2 retrieval performance. We have therefore simplified this concluding paragraph (here below) to state only that IASI-NG has a spatial resolution and sampling similar to IASI, ensuring the continuity of the SO2 time series, without making claims about its expected retrieval performance.

"The upcoming suite of Infrared Atmospheric Sounding Interferometers - New Generation (IASI-NG; Crevoisier et al., 2014) represents a major step forward for spaceborne IR SO2 monitoring. With the recent launch of the first IASI-NG instrument onboard Metop-SG-A1 (summer of 2025) and the availability of the first observations in 2026, the three planned IASI-NG sensors, ***with similar spatial resolution and sampling as IASI****, are expected to ensure the long-term continuity of the IASI mission well into the coming decades. This continuity will allow the extension of volcanic SO2 monitoring and the construction of a unique, multi-decadal time series based on consistent IR satellite observations"*

References:

Krueger, A. J., Sighting of El Chichon sulfur dioxide clouds with the Nimbus 7 total ozone mapping spectrometer, Science, 220,1377–9, doi:10.1126/science.220.4604.1377, 1983

Krueger, A. J., et al., Volcanic sulfur dioxide measurements from the Total Ozone Mapping Spectrometer (TOMS) instruments, J. Geophys. Res., 100, 14,057–14,076, doi:10.1029/95JD01222, 1995

Krotkov, et al., Day-Night Monitoring of Volcanic SO2 and Ash Clouds for Aviation Avoidance at Northern Polar Latitudes, Remote Sensing, 2021, https://doi.org/10.3390/rs13194003 , 2021

Li, C., et al., Version 1 NOAA-20/OMPS Nadir Mapper total column SO2 product: continuation of NASA long-term global data record, Earth Syst. Sci. Data, 16, 4291–4309, https://doi.org/10.5194/essd-16-4291-2024

Li, Can, et al., Version 2 Ozone Monitoring Instrument SO2 Product (OMSO2 V2): New Anthropogenic SO2 Vertical Column Density Dataset, Atmos. Meas. Tech., 13, 6175–6191, 2020 https://doi.org/10.5194/amt-13-6175-2020

References:

- Karagulian, F., Clarisse, L., Clerbaux, C., Prata, A. J., Hurtmans, D., and Coheur, P. F.: Detection of volcanic SO2, ash and H2SO4 using the IASI sounder, J. Geophys. Res., 115, D00L02, https://doi.org/10.1029/2009JD012786, 2010.
- Legras, B., Duchamp, C., Sellitto, P., Podglajen, A., Carboni, E., Siddans, R., Grooß, J.-U., Khaykin, S., and Ploeger, F.: The evolution and dynamics of the Hunga Tonga–Hunga Ha'apai sulfate aerosol plume in the stratosphere, Atmos. Chem. Phys., 22, 14957–14970, https://doi.org/10.5194/acp-22-14957-2022, 2022.
- Millán, L., Santee, M. L., Lambert, A., Livesey, N. J., Werner, F., Schwartz, M. J., Pumphrey, H. C., Manney, G. L., Wang, Y., Su, H., Wu, L., Read, W. G., and Froidevaux, L.: The Hunga Tonga-Hunga Ha'apai Hydration of the Stratosphere, Geophys. Res. Lett., 49, e2022GL099381, https://doi.org/10.1029/2022GL099381, 2022.
- Sellitto, P., Siddans, R., Belhadji, R., Carboni, E., Legras, B., Podglajen, A., Duchamp, C., and Kerridge, B.: Observing the SO2 and Sulfate Aerosol Plumes From the 2022 Hunga Eruption With the Infrared Atmospheric Sounding Interferometer (IASI), Geophys. Res. Lett., 51, e2023GL105 565, https://doi.org/10.1029/2023gl105565, 2024.
- Spurr, R. J. D., Christi, M., Krotkov, N. A., Choi, W.-E., Carn, S., Li, C., Kramarova, N., Haffner, D., Yang, E.-S., Gorkavyi, N., Vasilkov, A., Wargan, K., Torres, O., Loyola, D., Di Pede, S., Veefkind, J. P., Case, P., Schroeder, T., and Bhartia, P. K.: Solar Backscatter Ultraviolet (BUV) retrievals of mid-stratospheric aerosols from the 2022 Hunga Eruption, Atmos. Meas. Tech., 19, 993–1021, https://doi.org/10.5194/amt-19-993-2026, 2026.