



A full-mission TROPOMI SO₂ height dataset: enhanced sensitivity to low-altitude plumes and complementarity with IASI and PlumeTraj

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Abstract. Information on sulfur dioxide (SO₂) plume altitude is crucial for understanding volcanic events and their atmospheric and climatic impacts, constraining satellite SO₂ data, and improving aviation safety. While SO₂ column-density records have been routinely derived from UV nadir sensors for decades, plume-height retrievals remain challenging and have largely been limited to volcanic eruptions with relatively high SO₂ loadings. Here, we present the first global SO₂ plume-height dataset derived from the second UV spectral band of the TROPOspheric Monitoring Instrument (TROPOMI), covering 2018–2025. Building on our previous work (Fabris et al., 2026), retrievals were performed using an optimised implementation of the Look-Up Table Covariance-Based Retrieval Algorithm (LUT-COBRA), providing good sensitivity to low SO₂ amounts and a wide range of plume heights. We analyse global and regional SO₂ variability, including explosive eruptions, passive volcanic degassing, and anthropogenic emissions. We evaluate the dataset against SO₂ plume-height estimates from the Infrared Atmospheric Sounding Interferometer (IASI). Despite differences in vertical sensitivity and overpass time, the datasets generally agree well, with biases mainly within 0.7–4 km depending on observation conditions and plume properties. Comparisons with SO₂ height estimates from the trajectory-based PlumeTraj toolkit show excellent consistency, with biases below 1 km in most cases. The results highlight the complementarity of the three datasets and the potential benefit of combining them to obtain reliable information on SO₂ plume height across the whole atmosphere. The TROPOMI product provides a useful resource for monitoring and quantifying volcanic SO₂ emissions and assessing their environmental impacts.



1 Introduction

Sulfur dioxide (SO₂) is a key atmospheric trace gas emitted by anthropogenic sources, e.g., power plants, smelters, and oil refineries, as well as by volcanic activity (Fioletov et al., 2023). It is a precursor of sulfate aerosols and fine particulate matter, affecting ecosystems (Delmelle et al., 2001), human health (Orellano et al., 2021), aviation (Carn et al., 2009), air quality (Filonchyk et al., 2022), atmospheric chemistry (von Glasow et al., 2009), and climate (Robock, 2000; Kremser et al., 2016).

Satellite observations represent a reliable means of monitoring SO₂ emissions at the global scale. Most SO₂ datasets are based on measurements of vertical column densities (VCDs) retrieved from either thermal infrared (TIR) or ultraviolet (UV) nadir-viewing observations. Notable examples include SO₂ products derived from the Infrared Atmospheric Sounding Interferometer (IASI) onboard the Metop satellite series (Clarisse et al., 2012, 2026) starting from 2007 and the TROPospheric Monitoring Instrument (TROPOMI) onboard the Sentinel-5 Precursor platform (Theys et al., 2019) since May 2018. In contrast, SO₂ plume-height retrievals are less developed (especially in the UV) and many available datasets do not include altitude information. Yet, the knowledge of SO₂ height from space is crucial

- to further constrain satellite SO₂ data. There is a strong sensitivity of SO₂ VCD to the altitude, and the plume height is an important source of error if not accounted for (Yang et al., 2010; Clarisse et al., 2012; Bauduin et al., 2016).
- to support volcanological studies, by complementing ground-based observations (Esse et al., 2023), particularly for remote or hazardous volcanoes where measurements during eruptions are often difficult (not to say impossible). It is essential to estimate SO₂ mass and fluxes, which are widely used variables in volcanological studies to understand eruption dynamics and magmatic processes (Pardini et al., 2018; Esse et al., 2025a). The estimation of SO₂ fluxes usually requires information on the wind field (Theys et al., 2013), which is altitude dependent. Furthermore, for volcanic eruptions, the plume height is strongly related to the mass eruption rate, a key parameter to characterise eruptive activity (Mastin et al., 2009).
- to advance atmospheric and climate studies, as the altitude at which volcanic sulfur dioxide is injected strongly influences its transport, atmospheric lifetime, and conversion into sulfate aerosols. These processes affect atmospheric chemistry and ultimately determine the radiative forcing and climatic impact of volcanic emissions (Tilmes et al., 2018; Aubry et al., 2021; Axebrink et al., 2025; Toohey et al., 2025). This is relevant as there is a scientific consensus on the non-negligible role of minor volcanic eruptions on climate (Solomon et al., 2011; Santer et al., 2014; Schmidt et al., 2018).
- to inform aviation services (Brenot et al., 2014, 2021) such as Volcanic Ash Advisory Centres (VAACs) in case of an eruption affecting the air space, particularly when volcanic ash and SO₂ clouds are collocated (Thomas and Prata, 2011; Sears et al., 2013).

One way of estimating volcanic SO₂ plume altitude from space is by using trajectory-based methods. A good example is the PlumeTraj tool, which combines satellite VCD observations with atmospheric dispersion information to derive plume altitude and reconstruct time-resolved SO₂ emissions (Pardini et al., 2017, 2018; Queißer et al., 2019). PlumeTraj has proved



to be very powerful in deriving volcanic activity time-series data and understanding eruption precursors (Burton et al., 2021). Note, however, that the PlumeTraj results have hitherto been compared to ground-based measurements only in short-term case studies (Queißer et al., 2019), and no systematic long-term assessment has yet been performed, particularly for the retrieved SO₂ plume heights, motivating the comparison with independent satellite SO₂ height retrievals. In the thermal infrared, Carboni et al. (2016) presented an SO₂ plume-height product based on IASI observations for a series of volcanic eruptions. Clarisse et al. (2014) developed an alternative method to retrieve SO₂ heights, which was subsequently improved and applied to the complete IASI record to generate a long-term global SO₂ height dataset (Clarisse et al., 2026). This approach was also extended to observations from the Cross-track Infrared Sounder (CrIS) by Hyman and Pavolonis (2020). From UV satellite measurements and since the early studies by Yang et al. (2010) and Nowlan et al. (2011), comparable datasets have not been developed. Significant progress has nevertheless been achieved in recent years for retrieving SO₂ heights, using measurements from TROPOMI. Notably, the FP_ILM algorithm (Hedelt et al., 2019) now runs operationally but is limited to relatively large SO₂ loadings of at least 20 DU (1 DU or Dobson Unit equals 2.69×10^{16} molecules·cm⁻²). Theys et al. (2022) developed a look-up-table COBRA (LUT-COBRA) approach for TROPOMI band 3 (BD3; 310–326 nm) observations, improving retrieval sensitivity down to SO₂ columns of about 5 DU. More recently, Fabris et al. (2026) extended the LUT-COBRA approach to TROPOMI band 2 (BD2; 305–326 nm), exploiting the stronger SO₂ absorption at shorter UV wavelengths and the improved spectral sampling of the sensor. This development further enhanced the sensitivity of SO₂ height retrievals, reducing the detection limit to about 2 DU and opening the potential to monitor low SO₂ amounts down to the surface. It also improved precision by a factor of two, particularly in the upper troposphere–lower stratosphere (UTLS), and provided better accuracy under modest aerosol loading conditions.

In this paper, we apply our improved LUT-COBRA approach to the complete TROPOMI BD2 record from 2018 to 2025 to generate the first long-term global SO₂ plume-height dataset derived from nadir-viewing UV satellite observations. The dataset also includes associated SO₂ column information and is designed to provide a consistent view of both volcanic and anthropogenic SO₂ emissions over the TROPOMI mission. One objective of this study is also to compare the TROPOMI results with IASI height estimates. Clarisse et al. (2026) presented comparison results for three eruptive events indicating a general good agreement. Here, we aim to extend the comparison on a much larger scale, including 40 eruptive and degassing volcanoes. It is of scientific value to assess the TROPOMI and IASI SO₂ height retrievals and understand the possible reasons for discrepancies, having in mind the fundamentally different measurement sensitivity of both spectral regions. Importantly, IASI has limited sensitivity to SO₂ from volcanic degassing below 5 km. Therefore, to support the analysis, we compare TROPOMI and IASI to independent height estimates obtained from the PlumeTraj toolkit. We perform a comparison for the year 2020 (including 17 volcanic sites) and some eruptive events in other years. A better understanding of the respective strengths and limitations of each dataset is important for obtaining reliable SO₂ plume-height information, which is needed to constrain volcanic emissions and further understand their atmospheric evolution and potential climatic impacts. Overall, our results highlight the complementarity of these fundamentally different approaches for characterising SO₂ plume height across a wide range of volcanic conditions.



The manuscript is structured as follows. Section 2 describes the methodology used for processing the full TROPOMI BD2 timeframe and the uncertainties associated with our SO₂ height product. The results are then presented in Sections 3 and 4. In Section 3, we analyse the global dataset and highlight the major volcanic and anthropogenic SO₂ emissions over 2018–2025. In Section 4, we evaluate the product through comparisons with independent datasets, namely IASI and PlumeTraj, and discuss the strengths and limitations of each approach. Finally, the main conclusions and perspectives for future work are summarised.

2 Methods: TROPOMI SO₂ height retrieval

This section briefly describes the main improvements implemented in our fitting algorithm to process the full TROPOMI mission, as well as the uncertainties associated with the SO₂ height retrievals.

2.1 LUT-COBRA implementation and processing

The SO₂ height dataset presented in this study has been derived from TROPOMI UV observations. TROPOMI is a hyper-spectral nadir-viewing spectrometer onboard the polar-orbiting S-5P satellite (Veefkind et al., 2012), crossing the equator at approximately 13:30 local solar time and measuring solar radiation reflected by the Earth’s surface and backscattered by the atmosphere. It provides daily global coverage of atmospheric composition with a nadir spatial resolution of approximately 3.5 × 5.5 km². Here, we processed the data with LUT-COBRA, an iterative approach using a look-up table of precomputed SO₂ spectra to reproduce the measured SO₂ optical depths while treating all non-SO₂ spectral contributions (e.g., ozone) as a generalised error term. Originally developed for TROPOMI BD3 observations by Theys et al. (2022) and extended to BD2 by Fabris et al. (2026) (as introduced above), the algorithm jointly retrieves SO₂ plume height and vertical column density. As the retrieval methodology has been described in detail in Fabris et al. (2026), only the developments relevant to the generation of the present dataset are summarised below.

A first step was the implementation of BD2 LUT-COBRA within the Sentinel-5P Product Algorithm Laboratory infrastructure (S5P-PAL; <https://data-portal.s5p-pal.com/>), a dedicated processing environment designed to develop, test, and apply retrieval algorithms for TROPOMI. This was achieved in view of the future release of BD2 LUT-COBRA as a pre-operational PAL product. This required several technical adaptations of the original scripts, including optimisation of memory usage, revision of the inputs and outputs (e.g., pixel quality flagging), and support for multiprocessing, which significantly reduced the computational cost of the retrievals. Compared to the version presented by Fabris et al. (2026), different updates were also introduced to improve the robustness of the retrievals. In particular, the original filtering approach using fixed SO₂ slant column density (SCD) thresholds was replaced by a signal-to-noise criterion based on the ratio between the SO₂ SCD and its error (SCD_{err}), both obtained from the operational TROPOMI Level-2 COBRA product of Theys et al. (2021) and interpolated onto the BD2 grid. Only SO₂ observations with SCD/SCD_{err} ≥ 2.5 were processed. Since COBRA slant-column retrievals are typically associated with uncertainties of the order of 0.2 DU, this threshold remains sensitive to relatively weak SO₂ signals. In contrast to a fixed SCD threshold, it also naturally accounts for variations in retrieval uncertainty across the TROPOMI observations. Moreover, isolated SO₂ detections were discarded using a spatial-neighbourhood filter requiring at



least two neighbouring pixels above the detection threshold. This reduces noise in the SO₂ retrievals and decreases the processing time. Further improvements concerned the calculation of the effective surface albedo used by LUT-COBRA. In the original implementation, the effective albedo was derived in BD3 near 340 nm and subsequently interpolated to BD2. This occasionally led to unstable retrievals near plume edges. To mitigate this effect, neighbouring-pixel averaging was introduced during the interpolation step, resulting in smoother effective albedos and more robust plume-height retrievals.

2.2 Quality filtering and retrieval uncertainty

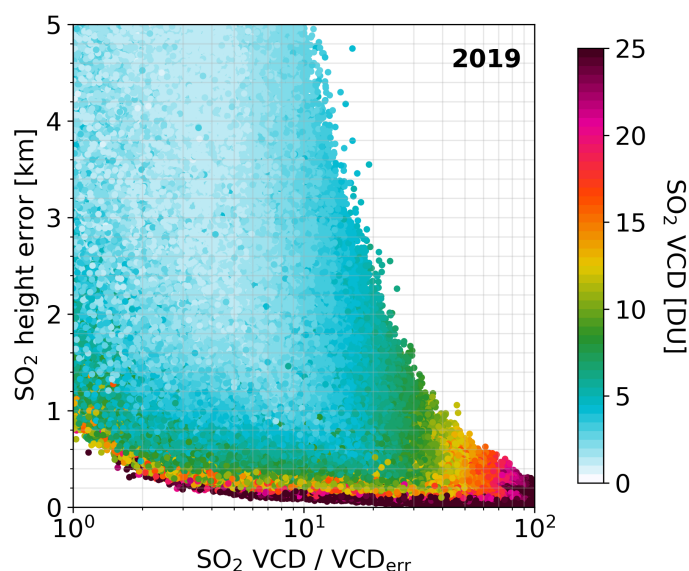


Figure 1. SO₂ height error for global TROPOMI data in 2019 as a function of the SO₂ VCD signal-to-noise ratio, with colours representing SO₂ VCD.

In the remainder of this section, we discuss the performance and uncertainty of the TROPOMI SO₂ height product. Fabris et al. (2026) have already demonstrated that using the BD2, instead of the more commonly used BD3, significantly improves the accuracy, precision, and sensitivity of the SO₂ height retrievals, particularly in the UTLS. Nevertheless, retrieval quality remains strongly dependent on the SO₂ signal strength and the pixel-selection criteria. Figure 1 presents the estimated SO₂ plume-height uncertainty in 2019 (taken as an example) as a function of the ratio between the retrieved SO₂ VCD and its random uncertainty (VCD/VCD_{err}), with colours indicating the retrieved SO₂ VCD. These results were generated using all retrievals satisfying a basic set of convergence and SO₂ detection criteria, namely the number of LUT-COBRA iterations below 10, SO₂ VCDs greater than 0.25 DU, $VCD/VCD_{err} \geq 1$, and either $SCD/SCD_{err} \geq 10$ or a fitting-window index greater than 1. The fitting-window index indicates which spectral window was used in the operational SO₂ slant-column retrieval (Romahn et al., 2024). The default fitting window (w1) covers the 310.5–326 nm spectral range, whereas alternative windows at longer wavelengths (w2: 325–335 nm and w3: 360–390 nm) are selected for larger SO₂ loadings. Because these alternative



windows generally yield larger SCD uncertainties, pixels associated with strong SO₂ signals may exhibit SCD/SCD_{err} values below 10 despite remaining highly reliable detections. Including retrievals with a fitting-window index greater than 1 therefore prevents high-SO₂ pixels from being rejected solely because of their lower slant-column signal-to-noise ratio. As expected, the estimated SO₂ height uncertainty in Figure 1 decreases rapidly with increasing SO₂ abundance and signal-to-noise ratio.

135 Retrievals associated with SO₂ columns below about 5 DU are generally characterised by VCD/VCD_{err} values below 10 and SO₂ height errors exceeding 1 km, whereas SO₂ columns larger than about 10 DU are typically associated with higher signal-to-noise ratios and plume-height uncertainties below about 1 km. Note that comparable observations were made for the other years of the TROPOMI record. This behaviour reflects the increasing information content available for the plume-height retrieval as the SO₂ absorption becomes stronger. Figure 1 further suggests that it is rather difficult to derive a single detection

140 limit (expressed in SO₂ VCD) for reliably retrieving the height of SO₂, as it depends largely on the conditions but also on the thresholds that one considers as acceptable in terms of height precision and VCD signal-to-noise ratio. For example, for an SO₂ height error threshold of 2 km and a minimum VCD SNR of 10, Figure 1 indicates that those will be fulfilled for pixels with SO₂ VCD typically larger than 4 DU. However, we note that averaging SO₂ height results from neighbouring pixels allow to reduce the noise on the data and improve the precision (but at the expense of a smoothing of the spatial details). This is further

145 described in the next section.

3 Global analysis of the long-term TROPOMI SO₂ plume-height dataset

In this section, we present and analyse the TROPOMI BD2 SO₂ height dataset and identify the major volcanic and anthropogenic SO₂ emissions observed from May 2018 to December 2025. Figure 2 gives a global multi-annual overview of the SO₂ plume heights retrieved throughout the TROPOMI mission. These maps were generated by applying a set of quality filters to

150 the individual SO₂ retrievals. We retained only SO₂ pixels with fewer than 10 fitting iterations, a plume height between 0.5 and 30 km with an uncertainty below 10 km, a VCD between 1 and 1000 DU, and a SCD signal-to-noise ratio (SCD/SCD_{err}) greater than or equal to 10, or a fitting-window index greater than 1. The filtered SO₂ pixels were subsequently averaged onto a 0.5° × 0.5° grid, and a 3 × 3 median filter was applied to reduce residual noise. In Figure 2, the main SO₂ emissions and transport pathways can be observed. The maps reveal a wide range of SO₂ sources, including major explosive eruptions such

155 as Raikoke (Russia) and Ulawun (Papua New Guinea) in 2019, La Soufrière (Saint Vincent and the Grenadines) in 2021, and Ruang (Indonesia) in 2024. They also highlight persistent SO₂ emissions associated with passive volcanic degassing, e.g., at Popocatepetl (Mexico) in 2020 and Etna (Italy) in 2025, as well as anthropogenic SO₂ hotspots over industrial regions such as Norilsk (Russia) in 2018 or parts of India in 2022. More detailed analyses can be performed by focusing on specific regions and time periods, where individual plumes can be examined more closely.

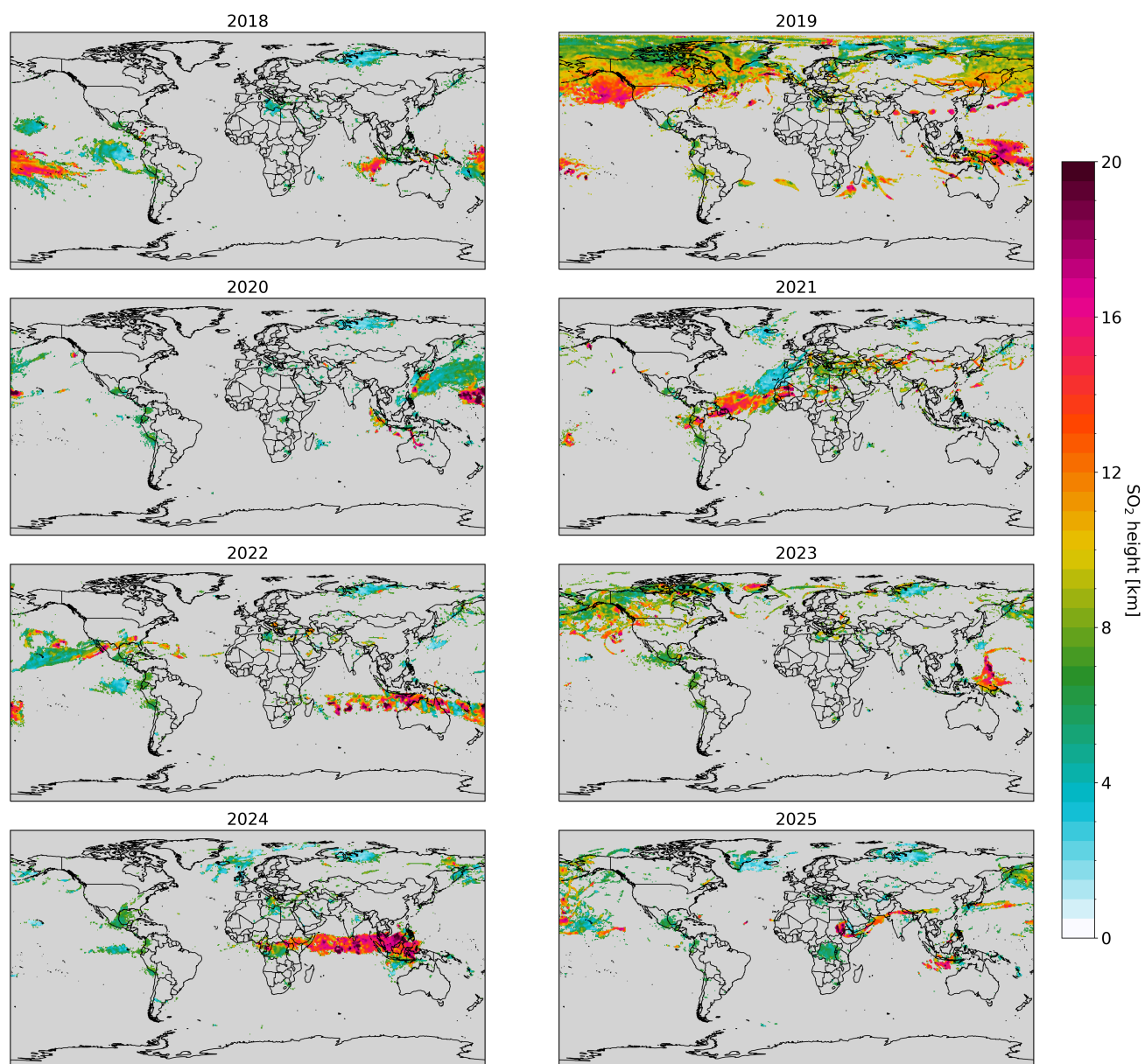


Figure 2. Annual global maps of SO₂ height retrieved from TROPOMI BD2 observations between 2018 and 2025. Retrievals were quality-filtered, averaged onto a $0.5^\circ \times 0.5^\circ$ grid, and smoothed using a 3×3 median filter.

160 As a demonstration of the product quality, Figure 3 displays SO₂ height and VCD results for three different cases. Figures 3a and d show the SO₂ plume from the explosive eruption of Taal volcano in the Philippines, observed by TROPOMI on 13 January 2020. This event marked the volcano's first major eruptive activity since 1977 and generated a substantial ash and gas plume, with ash altitudes reaching up to approximately 15 km (Jing et al., 2020). The ash cloud spread more than 70 km from the



volcano, affecting tens of thousands of people and causing major disruptions to air traffic and local infrastructure. Dozzo et al. (2025) estimated a total SO₂ mass of approximately 170 kt on that day using TROPOMI observations processed within Google Earth Engine. Here, we retrieve a total SO₂ mass of 182.87 kt and a median mass altitude of 8.3 km (corresponding to the altitude below which 50 % of the SO₂ mass is contained). As can be seen from Figure 3a, SO₂ was released into the atmosphere, at altitudes essentially from the surface to tropopause heights. Figures 3b and e illustrate a case of persistent degassing from Sabancaya volcano on 23 February 2022. Sabancaya has been one of the most active and continuously degassing volcanoes in Peru since the onset of its eruptive phase in 2016 (Machacca et al., 2023). Using TROPOMI observations acquired between April 2018 and March 2019, Fioletov et al. (2020) estimated annual SO₂ emissions of 335.06 ± 20.20 kt. Coppola et al. (2022) further showed that Sabancaya remained persistently active between 2016 and 2020, with highly variable SO₂ fluxes ranging from approximately 0.7–7.0 kt d⁻¹ and recurrent ash plumes reaching 0.5–5 km above the crater. For the analysed scene, our algorithm identifies a volcanic SO₂ cloud of approximately 2.95 kt, and derives a median mass altitude of 4.19 km. Finally, and in contrast to the volcanic examples, we show in Figures 3c and f, an anthropogenic SO₂ plume originating from the Baysun gas chemical complex (also known as the Boysun gas processing plant) in southern Uzbekistan. This source has become increasingly prominent in recent years and is clearly visible in the satellite observations, although not listed in the most recent SO₂ emission catalogue of Fioletov et al. (2023). Based on our TROPOMI BD2 dataset, the total annual SO₂ mass associated with this source increased from 0.88 kt in 2018 to 186.90 kt in 2025, accounting for approximately 2.89 % of the global SO₂ mass detected that year. In particular, on 25 June 2025, we retrieve a total SO₂ mass of 2.95 kt and a median height of 1.93 km (i.e., close to the surface). This case study highlights the significant contribution that human activities can make to the global SO₂ budget and underscores the importance of monitoring emissions in the lower troposphere. Overall, the three cases cover very different SO₂ loadings (Figures 3d–f), showing that our product provides realistic SO₂ plume-height information over a broad range of VCDs.

We further analysed the temporal evolution of the SO₂ mass and identified the main volcanic SO₂ emissions captured by TROPOMI between 2018 and 2025. Daily SO₂ mass distributions were generated using 1 km plume-height bins between 0 and 30 km. For each quality-filtered SO₂ pixel, the mass was estimated from the retrieved VCD and pixel area, and assigned to the corresponding altitude bin. The contributions from all pixels were then summed up to obtain daily SO₂ mass profiles. Figure 4 presents the resulting time series over the first 7.5 years of the TROPOMI mission. For each period, the upper panel shows the vertical SO₂ mass distributions, while the lower panel displays the corresponding total SO₂ mass together with the contributions below and above 5 km altitude. In Figure 4a, covering May 2018 to December 2021, the record is dominated by the explosive eruption of Raikoke during the summer of 2019. The highest daily SO₂ mass was indeed observed on 26 June 2019, reaching 3.96×10^3 kt, with the corresponding mass distribution peaking at an altitude of about 9.59 km. Over 2018–2021, 27.69×10^3 kt of SO₂ was found below 5 km, compared to 50.37×10^3 kt above 5 km, indicating that 64.53 % of the total SO₂ mass detected by TROPOMI was associated with plume heights exceeding 5 km. This predominance of high-altitude SO₂ is largely explained by the Raikoke and Ulawun eruptions, which injected substantial amounts of SO₂ into the UTLS (Cai et al., 2022; Vernier et al., 2024; McKee et al., 2021). Note, however, that weaker passive SO₂ emissions may partly remain below the detection limit of the product and are therefore not fully accounted for in these estimates.

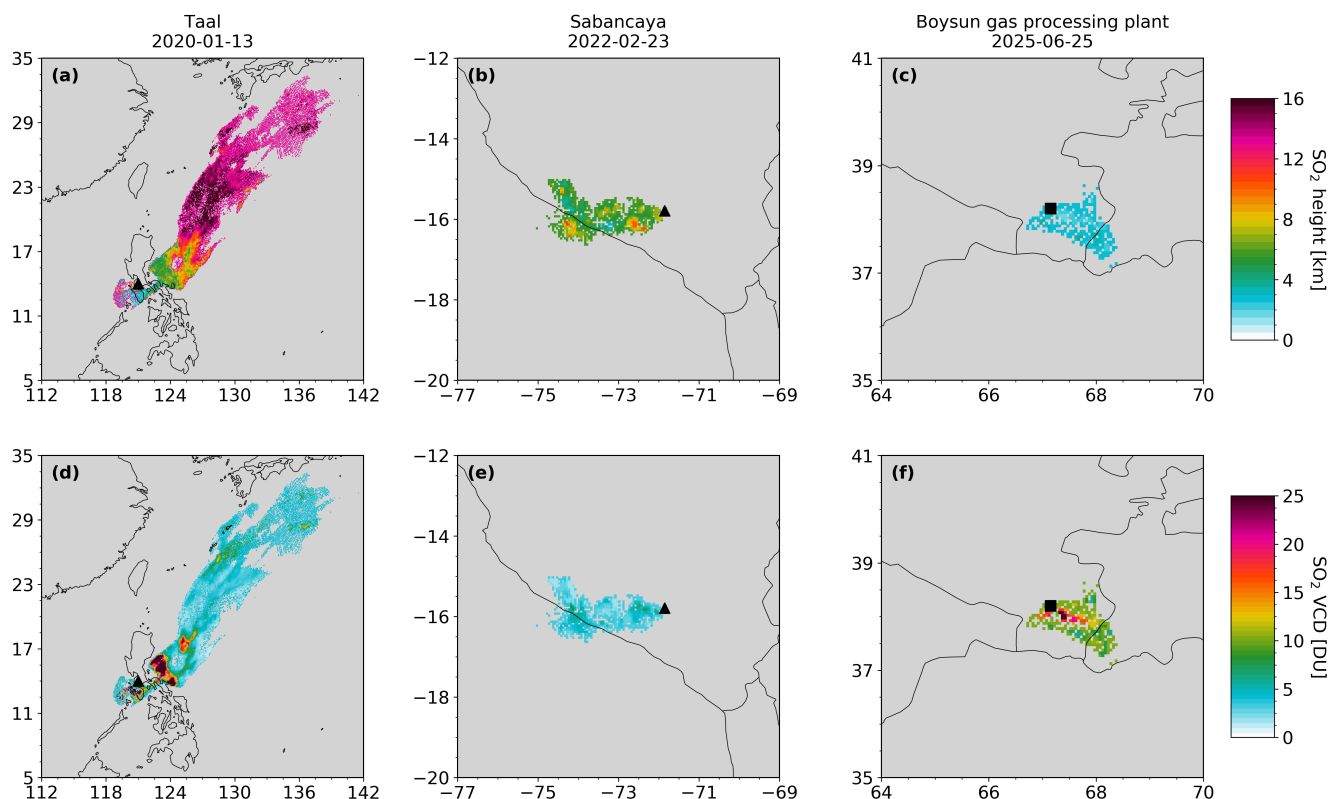


Figure 3. SO₂ height and VCD maps for three representative emission cases. (a)–(c) SO₂ heights for the 2020 explosive eruption of Taal (Philippines, elevation: 0.311 km), the 2022 passive degassing of Sabancaya (Peru, elevation: 5.960 km), and the 2025 anthropogenic emissions from the Boysun gas processing plant (Uzbekistan, elevation: ~1–2 km), respectively. (d)–(f) Corresponding SO₂ VCDs. Triangles indicate the volcano locations, while the square indicates the location of the anthropogenic source.

Similarly, Figure 4b shows the results from TROPOMI between 2022 and 2025. Here, the highest daily SO₂ mass was observed on 13 April 2023, reaching 598.58 kt, of which 492.36 kt was attributed to the Sheveluch eruption, with the SO₂ mass distribution peaking at 6.72 km. The remaining mass was mainly associated with persistent degassing from Sabancaya and Popocatepetl, as well as anthropogenic emissions from Norilsk (Russia). The integrated SO₂ mass detected by TROPOMI over this period amounts to 25.67×10^3 kt, of which 16.53×10^3 kt (64.40 %) was associated with plume heights below 5 km and 9.14×10^3 kt (35.60 %) with plume heights above 5 km. In contrast to Figure 4a, major explosive eruptions no longer dominate the global SO₂ budget. Instead, persistent volcanic degassing and anthropogenic emissions contribute considerably to the observed total SO₂ mass. The increasing contribution of low-altitude SO₂ is particularly evident in 2025 and is mainly explained by passive degassing from Nyiragongo (DR Congo), accounting for approximately 33.73% of the global SO₂ emissions, together with anthropogenic emissions from Norilsk (6.76%).

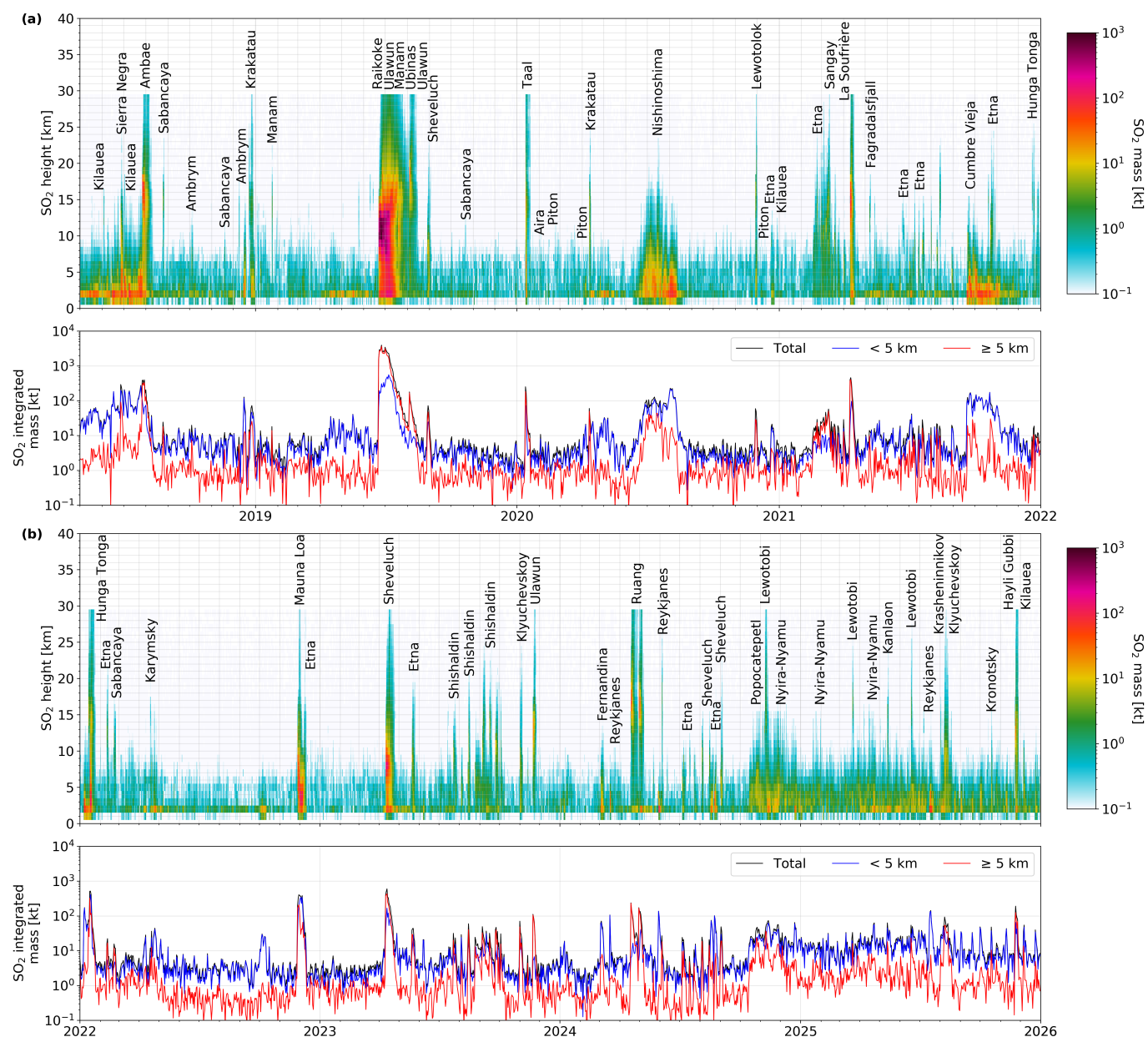


Figure 4. TROPOMI BD2 SO₂ mass time series over (a) 2018–2021 and (b) 2022–2025. For each period, the upper panel presents the daily vertical SO₂ mass distributions, whereas the lower panel shows the corresponding total SO₂ mass (black) and the contributions from altitudes below (blue) and above (red) 5 km. Major volcanic events associated with the main SO₂ mass peaks are indicated.

Our TROPOMI BD2 product is broadly consistent with the recent global SO₂ dataset derived from IASI by Clarisse et al. (2026). Most of the volcanic eruptions identified in the IASI record are also clearly detected by TROPOMI, including e.g.,



Ambae (2018), Krakatau (2018), Nishinoshima (2020), Lewotolok (2020), Sangay (2021), Cumbre Vieja (2021), Hunga Tonga (2022), Mauna Loa (2022), Shishaldin (2023), Lewotobi (2024–2025), and Hayli Gubbi (2025). In addition to these eruptions, both datasets also capture frequent minor SO₂ emissions over the years from volcanoes such as Sabancaya, Kilauea, Reykjanes, Nyiragongo, and Sheveluch. We also find that tropical eruptions generally reach higher altitudes than extratropical eruptions, in agreement with Clarisse et al. (2026). Tropical eruptions such as Ambae (2018), Taal (2020), La Soufrière (2021), Hunga Tonga (2022), Ruang (2024), and Lewotobi (2024–2025) are associated with SO₂ masses reaching 15–20 km altitude or higher, whereas most extratropical eruptions are characterised by lower plume altitudes. This contrast reflects differences in tropopause altitude between tropical and extratropical regions. The comparison with IASI is particularly relevant as it illustrates the complementarity of UV and TIR satellite observations. IASI provides a long-term, twice-daily global record with strong sensitivity to volcanic SO₂ plumes in the free troposphere and UTLS, including during night-time and at high latitudes, but its sensitivity decreases at lower altitudes, particularly below 5 km, due to water vapour absorption and an overall reduced thermal contrast. In comparison, TROPOMI uses the backscattered and reflected solar radiation and therefore does not cover polar night. It is also largely affected at high solar zenith angles, where reduced UV radiances, longer atmospheric light paths, enhanced ozone absorption, and increased sensitivity to clouds can degrade the retrieval. As a result, some high-latitude eruptions identified in the IASI record are only partially observed by TROPOMI, or may even remain undetected during periods of polar night. Under favourable illumination conditions, however, the high spatial resolution and enhanced sensitivity of the TROPOMI BD2 retrieval allow lower-altitude SO₂ plumes from passive volcanic degassing and anthropogenic sources to be detected and characterised more effectively. This is a crucial advantage knowing that a large portion of SO₂ is emitted below 5 km, as indicated in Figure 4.



230 4 Evaluation against IASI and PlumeTraj

In the following sections, we evaluate our TROPOMI SO₂ height product against other datasets for more than 40 volcanic case studies worldwide, spanning both explosive eruptions and passive degassing episodes. The identifier (ID), name, location, and summit elevation of each volcano are listed in Table A1. For each case, the comparison is performed for a fixed geographical domain carefully selected to cover most of the SO₂ plume while minimising the influence of other volcanoes. Specific analysis periods are defined accordingly. A distinction is made between "event-based emission" (eruptions of few days to weeks) and "continuous emission", i.e., degassing volcanoes with an analysis period up to one year. Details are given in Table A2 and Figure A1. Comparisons with IASI observations (see Section 4.1) and independent estimates from the PlumeTraj modelling tool (see Section 4.2) are presented. Note that detailed results of these analyses can be found in the Supplementary Material.

4.1 Comparison with IASI observations

240 We first compared our TROPOMI SO₂ height product with IASI observations for several volcanic cases. Acknowledging the fact that a direct comparison is not possible due to observation time difference, we computed daily SO₂ height estimates representative of the studied areas for both instruments and compared those over the analysis period. We used the IASI SO₂ height dataset of Clarisse et al. (2026), considering only observations from the descending (AM) orbit, with a nominal Equator crossing time of 09:30 local solar time. Tests using observations from the ascending (PM; 21:30 local solar time) orbit showed little impact on the results at mid- and high latitudes. Differences were more noticeable in the tropics, where the AM orbit provides the closest temporal coincidence with the TROPOMI overpass (13:30 local solar time). We therefore considered the AM data throughout the analysis. These IASI observations were filtered based on the hyperspectral range index (HRI), which measures the strength of the SO₂ spectral signature relative to background spectral variability. Following the recommended selection criteria, we used a threshold of HRI > 5 to reduce noise from weak SO₂ detections. Although lower thresholds increase the extent of the plume, they also include noisier observations. Nevertheless, sensitivity tests using HRI thresholds of 1 and 3 showed only minor changes in the results. We also applied quality filters on the SO₂ VCD (1–1000 DU) and plume height (0.5–30 km) for consistency with the TROPOMI analysis of Section 3. Furthermore, only observations containing at least 2 IASI pixels and 24 TROPOMI pixels were exploited. These thresholds ensure a sufficient number of observations for the daily statistics and account for the different spatial resolutions of the two instruments. When observations from multiple Metop platforms were available on a given day, the instrument providing the largest spatial coverage over the volcanic region was selected. For both sensors, daily SO₂ mass-altitude distributions were calculated, and the median mass altitude (Q50) was used as the representative plume height, while the 10th (Q10) and 90th (Q90) percentiles characterise the vertical spread of the SO₂ mass. Throughout this section, the reported bias corresponds to the median of the daily Q50 height differences between TROPOMI and IASI. It should be noted that the use of fixed latitude-longitude domains can lead to sampling differences simply because the plumes may be transported between the two satellite overpass times. However, it has the advantage of being applicable to all 40 volcanic case studies and provides some useful information, as will be shown below.



Examples of results are provided in Figure 5, for (a) Sangay, (b) Shishaldin, (c) Reykjanes, and (d) Lewotobi. Sangay is one of the most active volcanoes in Ecuador and has been characterised by persistent eruptive activity since 2019, including frequent ash emissions, sustained SO₂ degassing, and recurrent explosive events (Vasconez et al., 2022). Here, we focus on

265 March 2021, a period of enhanced activity marked by continuous degassing episodes and major eruptions on 6–7 and 11 March 2021 (Global Volcanism Program, 2021a). Both TROPOMI and IASI capture the resulting increase in SO₂ plume altitude, with maximum heights observed during the first half of March followed by a gradual decline towards the end of the month. Overall, the two datasets show a similar temporal evolution, although TROPOMI generally retrieves lower SO₂ heights than IASI, with a median bias of -1.99 ± 1.71 km. Despite a very good agreement on some days, interestingly,

270 relatively large discrepancies of about 3–5 km are observed during the 6–7 March eruptive episode, whereas the agreement is noticeably better during the major eruption of 11 March, with differences typically limited to about 2–3 km. A possible explanation is the presence of volcanic ash, as reported by Global Volcanism Program (2021a), which may affect the TROPOMI retrievals depending on its abundance and altitude relative to the SO₂ plume. Nevertheless, the overall good agreement may be favoured by the high elevation of the volcanic source (5.286 km above sea level), which places a large fraction of the

275 SO₂ plume in the free troposphere, where TIR measurements are less affected by water-vapour absorption. Note that by the end of March, as the SO₂ detected within the selected domain is predominantly located at lower altitudes, IASI provides fewer observations, whereas TROPOMI remains sensitive to low-altitude SO₂ emissions from the volcano. On Figure 5b, a somewhat more variable agreement is found for Shishaldin, an active volcano located in the Aleutian Islands, Alaska (USA). Following nearly three years of relative quiescence, the volcano produced several explosive events between July and November

280 2023, generating substantial ash and SO₂ emissions. Ash plumes reached altitudes of up to about 14 km above sea level, while satellite observations indicated persistent SO₂ emissions throughout the eruptive period (Global Volcanism Program, 2023). As for Sangay, TROPOMI generally retrieves lower SO₂ heights than IASI, with a median difference of -2.73 ± 2.37 km. The relatively large spread of the differences likely reflects the thin and dispersed structure of many of the SO₂ plumes, for which partial pixel-filling effects may become important, particularly near plume edges. Such effects have previously been

285 reported to affect UV SO₂ retrievals and can introduce biases in the retrieved plume height, especially during periods of weaker degassing, when the SO₂ plume becomes more diffuse and the mean SO₂ columns are lower (Yang et al., 2010). In contrast, the agreement is slightly better during explosive episodes, such as those observed around 15 August, 5 September, 25 September, and 6 October 2023, when both instruments retrieve elevated SO₂ plumes associated with larger SO₂ columns. Note that fewer TROPOMI observations are available from mid-October to early November. This period corresponds to increasing

290 solar zenith angles and the onset of polar-night conditions at the latitude of Shishaldin. Some of the SO₂ observed in early November may also originate from Klyuchevskoy (Russia), whose plume was transported over the Shishaldin region. This can lead to increased uncertainties in the SO₂ height retrievals. On Figure 5c, Reykjanes also represents an interesting example. This volcanic system, in southwestern Iceland, reactivated in March 2021 after more than 800 years of quiescence. Since then, recurrent eruptive episodes have generated persistent SO₂ emissions (Gottlieb, 2026). Here, we analyse its activity in August

295 2024, a period characterised by low-altitude SO₂ emissions. Both TROPOMI and IASI derive plume heights predominantly below 5 km. TROPOMI retrieves again lower SO₂ heights than IASI, with a median difference of -2.32 ± 0.97 km. However,



IASI provides fewer observations towards the end of August and beginning of September, when the SO₂ plume remains confined to the lower troposphere. Such low-altitude conditions are challenging for thermal infrared observations, as discussed previously. This example therefore shows that TROPOMI is able to detect continuous low-altitude degassing. Conversely, the November 2024 eruption of Lewotobi, Indonesia (Figure 5d), provides a clear contrast with the Reykjanes case. Relatively large discrepancies are observed between the two sensors, with a median bias of -5.87 ± 4.03 km. IASI estimates the SO₂ heights around 15–16 km during the first eruptive phase of November and around 10–12 km during the second phase later in the month, whereas TROPOMI derives lower and more variable values. These differences may partly reflect the different vertical sensitivities of the two instruments. In particular, IASI may be less sensitive to low-altitude portions of the SO₂ plume because of lower SO₂ concentrations and stronger water-vapour interference, so that the retrieved heights predominantly represent the higher-altitude part of the plume. In contrast, TROPOMI remains sensitive to lower-altitude SO₂, resulting in lower median SO₂ heights when considering the plume as a whole. Furthermore, in the UTLS, the sensitivity of UV measurements to SO₂ height is expected to decrease (Yang et al., 2010). Although the use of shorter UV wavelengths in BD2 (compared to BD3) improves the sensitivity at these altitudes, as shown by Fabris et al. (2026), it is likely to remain lower than that of TIR measurements. This example thus highlights the complementarity of the two instruments, with IASI providing valuable information in the UTLS when the UV retrieval becomes more challenging. Note that the presence of relatively large amounts of volcanic ash may contribute to these observed differences. Finally, a general remark for all cases in Figure 5 relates to the variability in the SO₂ height. As explained above, the error bars represent the vertical spread of the SO₂ mass profiles from TROPOMI and IASI. From Figure 5, it appears that the vertical extent of the SO₂ plumes is generally lower for IASI than for TROPOMI, and often points to a single altitude. We further investigate this point below.

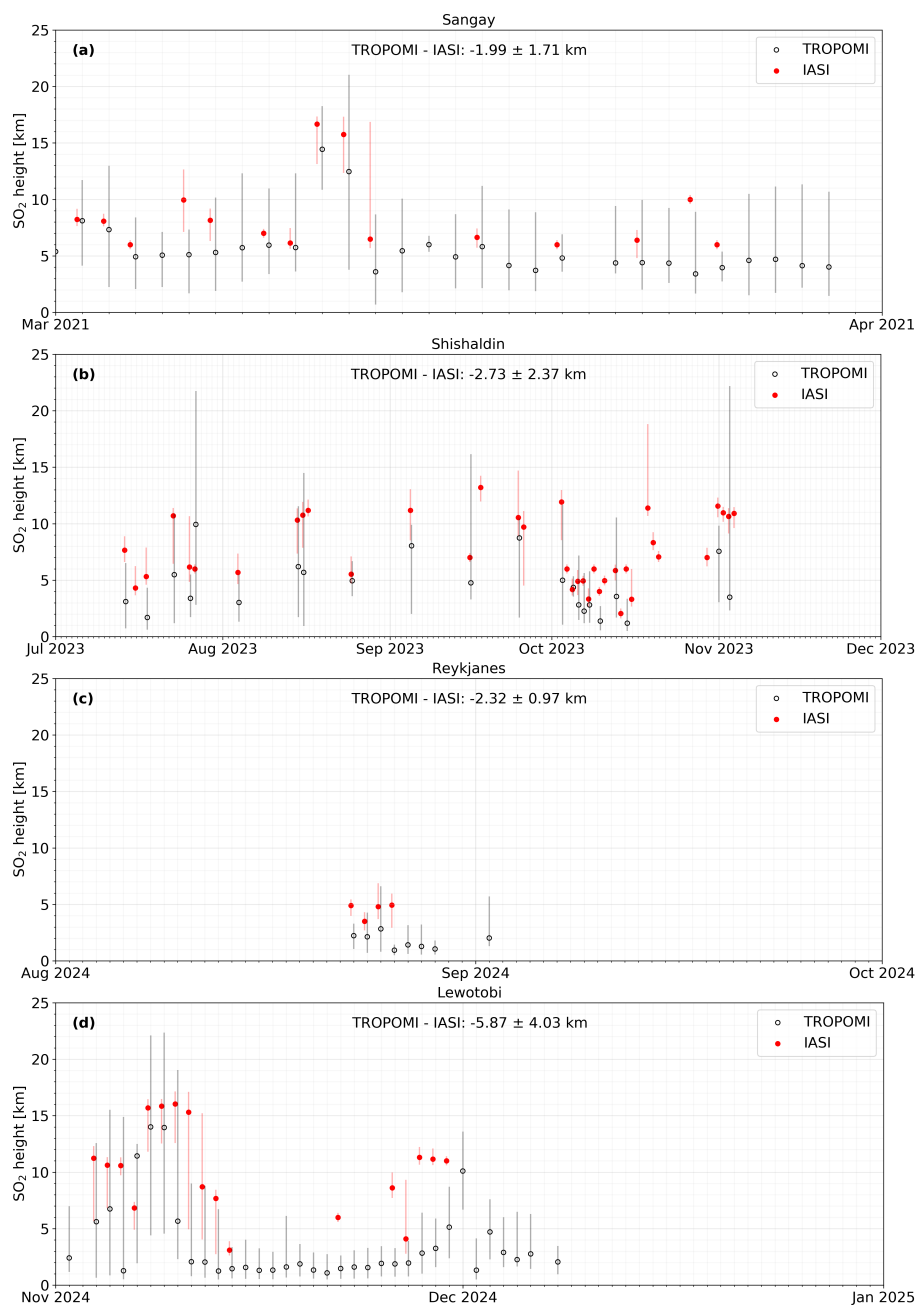


Figure 5. Time series of daily SO₂ height from TROPOMI (black) and IASI (red) for Sangay in 2021 (a), Shishaldin in 2023 (b), and Reykjanes (c) and Lewotobi (d) in 2024. The dots are the Q50 height estimates and the error bars indicate the Q10–Q90 ranges of the SO₂ mass profiles. The median difference $\pm$ standard deviation between TROPOMI and IASI SO₂ heights is indicated at the top of each panel.



We extended these comparisons to different volcanic events between 2018 and 2025, using the same approach as described above, with the geographical domains and analysis periods provided in Table A2. The results are summarised in Figure 6, where the marker contours (dotted or solid) indicate the type of SO₂ emission (i.e., event-based or continuous emissions), the colour represents the median Q50 SO₂ height difference between TROPOMI and IASI, and the marker size is proportional to the median TROPOMI SO₂ height. Note that, for volcanoes analysed over several periods, the results shown here correspond to the median of the values obtained for the individual periods, and are labelled as continuous-emission cases. Considering all analysed cases, the median bias is -2.39 ± 1.47 km, confirming the systematic tendency of TROPOMI to retrieve lower SO₂ plume heights than IASI. Most eruptions lead to median SO₂ height differences between approximately -1 and -4 km. The smallest bias is found for the December 2018 Krakatau eruption (-0.71 km), whereas the largest discrepancies are observed for explosive events like the January 2022 Hunga Tonga eruption (-11.00 km). The results for Hunga Tonga are not surprising. The combination of very high SO₂ plume heights and large amounts of co-emitted aerosols (Carn et al., 2022; Sellitto et al., 2024) leads to a failure of our retrievals, as the conditions deviate strongly from the algorithm assumptions.

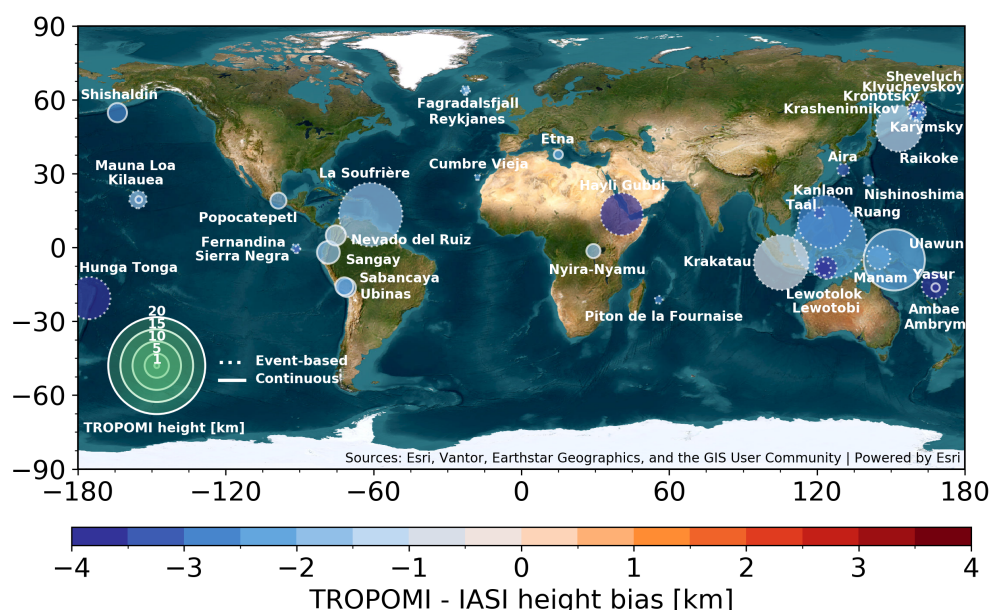


Figure 6. Comparison of SO₂ heights retrieved from TROPOMI and IASI for volcanic events (as in Figure 5) between 2018–2025. Circle size is proportional to the TROPOMI median Q50 SO₂ height, while colour indicates the median bias between TROPOMI and IASI. Outlines are solid or dotted depending on whether the emission is continuous or event-based, respectively. Map data from Esri World Imagery (2026).

Figure 7a further compares TROPOMI and IASI plume heights using the median Q50 derived from the daily SO₂ mass distributions, with different markers depending on the event type. Note that the classification between event-based and continuous emission is only to give a volcanic activity context and can be sometimes subject to interpretation. Consistent with Figure 6, a statistically significant negative bias of -2.11 km is observed between TROPOMI and IASI for the sites classified as continuously emitting volcanoes, whereas a more pronounced negative bias of -2.67 km is seen for event-based cases. In



Figure 7b, we compare the Q90 height estimates (the altitude leaving 90 % of the SO₂ mass underneath) instead of Q50 (as in Figure 7a). The rationale behind this is that Q90 might be a better metric for comparing datasets with different vertical sensitivity, especially for tropical sites where infrared sensors like IASI are less sensitive to lower tropospheric parts of the plume than UV sensors such as TROPOMI. As can be seen, the comparison when we consider the upper part of the SO₂ mass distribution leads to a better agreement between TROPOMI and IASI. It is enlightening to confront those results with the estimated systematic uncertainties of TROPOMI (1.91 km; Fabris et al., 2026) and IASI (1–2 km; Clarisse et al., 2026). When considered in quadrature, the combined uncertainty is of about 2–3 km. Therefore, Figure 7b suggests that TROPOMI and IASI SO₂ heights agree within their mutual uncertainties. It is important to note that, compared to Q50, the Q90 bias is reduced both for the continuous emission sites (-0.13 km) and the eruptive events (-0.30 km). For the continuous emission sites, it likely reflects the fundamentally different vertical sensitivity between UV and TIR retrievals. For the eruptive events, we find the largest mean absolute differences between the Q50 and Q90 heights for major explosive eruptions, including Lewotobi, Hunga Tonga, Ambae, Karymsky, Lewotolok, Hayli Gubbi, Sierra Negra, and Ambrym. For those cases, it is likely that the presence of large amounts of aerosols (notably UV absorbing aerosols) in the core of the plume plays a role in the larger negative bias of TROPOMI relative to IASI.

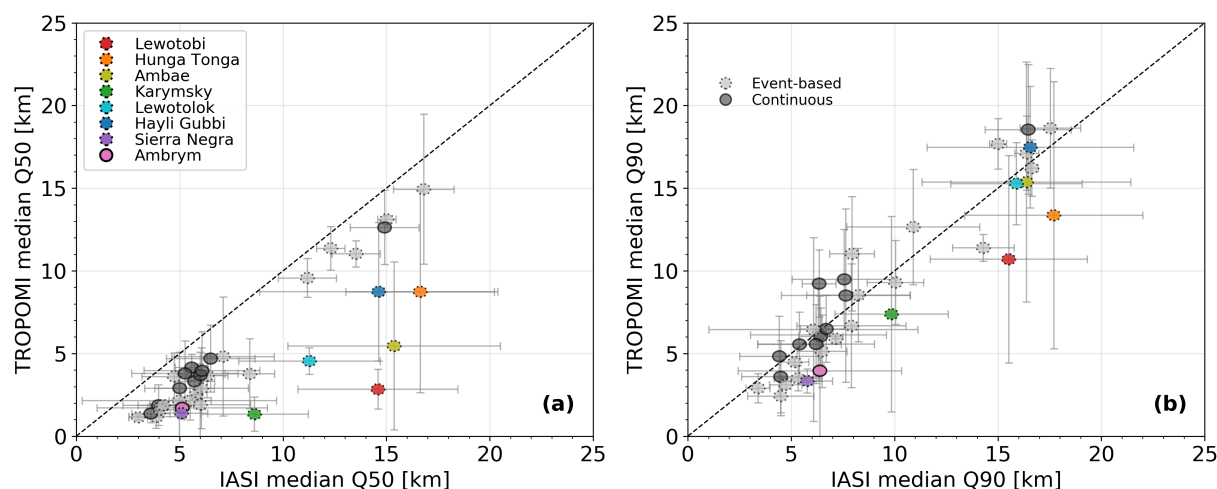


Figure 7. Comparison of median (a) Q50 and (b) Q90 SO₂ heights derived from TROPOMI and IASI for all volcanic events considered in this study. Marker styles distinguish event-based eruptions (dotted circles) from continuous emissions (solid circles). The eight largest absolute TROPOMI-IASI differences, based on the mean absolute difference between the Q50 and Q90 plume heights, are indicated using different colours. Vertical and horizontal error bars represent the standard deviations of the median SO₂ heights derived from TROPOMI and IASI, respectively. The dashed line corresponds to the one-to-one relationship.



4.2 Comparison with PlumeTraj estimates

As the previous analyses revealed considerable variability in the agreement between TROPOMI and IASI across the different case studies, we performed additional comparisons with PlumeTraj, a trajectory-based framework. PlumeTraj uses satellite SO₂ VCD observations from the operational TROPOMI BD3 product (Theys et al., 2025) to identify the SO₂ plume pixels and combines them with forward or backward trajectories computed using the HYSPLIT Lagrangian dispersion model (Stein et al., 2015) to derive volcanic SO₂ plume altitude, emission time, and plume age (Pardini et al., 2017, 2018; Quei er et al., 2019). As briefly introduced in Section 1, the approach exploits vertical wind shear: because air parcels released at different altitudes follow different transport pathways, only trajectories initiated at specific altitudes are consistent with both the observed SO₂ plume position and the volcanic source. By identifying these trajectories, PlumeTraj thus estimates plume altitude and emission time, and reconstructs a time-resolved SO₂ emission history. This approach differs fundamentally from the TROPOMI and IASI spectroscopic retrievals, as PlumeTraj infers plume altitude from atmospheric transport using only satellite pixel geolocation and observation time. Although TROPOMI SO₂ VCDs are used to identify pixels containing SO₂, their values are not used to determine the PlumeTraj plume heights, which are derived from the trajectory analysis. As a result, it is largely insensitive to radiative-transfer effects that can affect satellite SO₂ height retrievals, such as aerosol loading, plume dispersion, water-vapour absorption, and thermal-contrast effects. However, the inferred SO₂ plume altitudes remain sensitive to uncertainties in the meteorological wind fields and may become ambiguous under weak-shear or complex-flow conditions. This approach also assumes passive tracer transport and therefore neglects chemical transformations and aerosol microphysical processes. The different physical basis of PlumeTraj provides an opportunity to assess whether the plume-altitude patterns and systematic differences identified in the TROPOMI and IASI datasets can be further understood. To this end, we used an SO₂ product for 2020, covering volcanic degassing and several major eruptions, including Taal, Krakatau, Nishinoshima, and Lewotolok (Esse et al., in prep), complemented by previously published data for Kilauea in 2018 (Delbrel et al., 2024), La Soufriere (Esse et al., 2024) and Cumbre Vieja in 2021 (Esse et al., 2025b), and Mauna Loa in 2022 (Esse et al., 2025a). For consistency, the same filtering criteria as for the TROPOMI dataset (see Section 4.1) were applied, namely SO₂ VCDs between 1 and 1000 DU, SO₂ heights between 0.5 and 30 km, and a minimum of 24 SO₂ pixels.

We first examine the June–August 2020 SO₂ emissions from Nishinoshima, a volcanic island located approximately 1000 km south of Japan. Over this period, Nishinoshima continuously emitted ash and SO₂ plumes reaching altitudes of up to about 8 km (Global Volcanism Program, 2020; Williams and Ramsey, 2022) and dispersing across large parts of the western North Pacific (Park et al., 2025). The combination of persistent low-altitude degassing and higher-altitude eruptive phases makes Nishinoshima a particularly useful test case to compare SO₂ height estimates from TROPOMI, IASI, and PlumeTraj.

Figure 8 presents the daily SO₂ plume heights retrieved from the three datasets during the summer of 2020. As in Section 4.1, the median altitude of the SO₂ mass distribution is used as the representative plume height, while the vertical bars indicate the Q10–Q90 range. Also shown in Figure 8 are the daily differences between TROPOMI and PlumeTraj and between IASI and PlumeTraj, together with the daily PlumeTraj standard deviation (shaded area). The three datasets capture a consistent temporal evolution throughout the eruption, with relatively low plume altitudes during June, a gradual increase throughout July, and



maximum plume heights reached around 20–22 July before decreasing towards the end of the eruptive period. Overall, we find an excellent agreement between TROPOMI and PlumeTraj, with a median Q50 difference of -0.29 ± 0.99 km. In contrast, IASI generally retrieves higher SO₂ altitudes than both TROPOMI and PlumeTraj. Over the same period, the median difference between IASI and PlumeTraj is 2.70 ± 1.16 km. As SO₂ altitudes decrease towards the end of August, IASI observations also become increasingly sparse, reflecting the difficulty of detecting SO₂ near the surface. This behaviour is consistent with the reduced sensitivity of TIR observations to low-altitude SO₂, as already outlined in Section 4.1. We also note that the PlumeTraj standard deviation reaches up to 5–6 km on some days. This reflects situations in which multiple trajectory solutions are compatible with the observed plume location, leading to increased uncertainty in the inferred plume altitude. Such ambiguities typically arise under complex wind-shear conditions and may result in considerably different plume-height solutions from one pixel to another. Despite the overall agreement between TROPOMI and PlumeTraj, several individual days exhibit larger discrepancies, with absolute differences occasionally approaching 2.5 km. These cases are discussed in more detail below.

SO₂ height maps are shown in Figure 9 for three selected days during the Nishinoshima eruption. The first two cases correspond to days where the TROPOMI-PlumeTraj SO₂ height difference differs from the median daily bias (-0.29 ± 0.99 km) by more than two standard deviations, whereas the third case was selected to illustrate a more representative level of agreement.

Overall, the three datasets reproduce the main spatial features of the SO₂ cloud, but differ in both the retrieved plume heights and the extent of the detected emissions. In particular, parts of the SO₂ cloud identified by TROPOMI and IASI are not captured by PlumeTraj, especially at larger distances from the volcanic source. This is partly because trajectories are calculated only up to a plume age of 30 h, so that older and more distal parts of the plume may not be captured. In addition, when multiple height-age solutions are obtained for a given pixel, the youngest solution is selected in this study, as this has generally been found to provide results consistent with neighbouring pixels, although it may not always represent the correct solution. The agreement between the products also varies significantly with plume altitude and dispersion. On 16 July 2020, PlumeTraj retrieves globally lower SO₂ heights than both TROPOMI and IASI over much of the plume. This is likely due to the temporal evolution of the wind field, which resulted in multiple possible PlumeTraj solutions at different altitudes, including lower-altitude solutions than those retrieved by TROPOMI and IASI. In contrast, on 21 July and 2 August 2020, the agreement becomes more variable, with PlumeTraj showing closer agreement with TROPOMI in some regions and with IASI in others. In particular, lower-altitude parts of the SO₂ plume generally agree better with the TROPOMI retrievals, whereas higher-altitude regions tend to be more consistent with the IASI observations. These examples align with the Q50 time series shown in Figure 8 and further suggest that PlumeTraj often provides an intermediate constraint between the UV and TIR retrievals. At the same time, they illustrate that the relative agreement between the three approaches can vary within a single SO₂ cloud, reflecting the combined influence of plume altitude and density, atmospheric dispersion, and the transport-based nature of PlumeTraj.

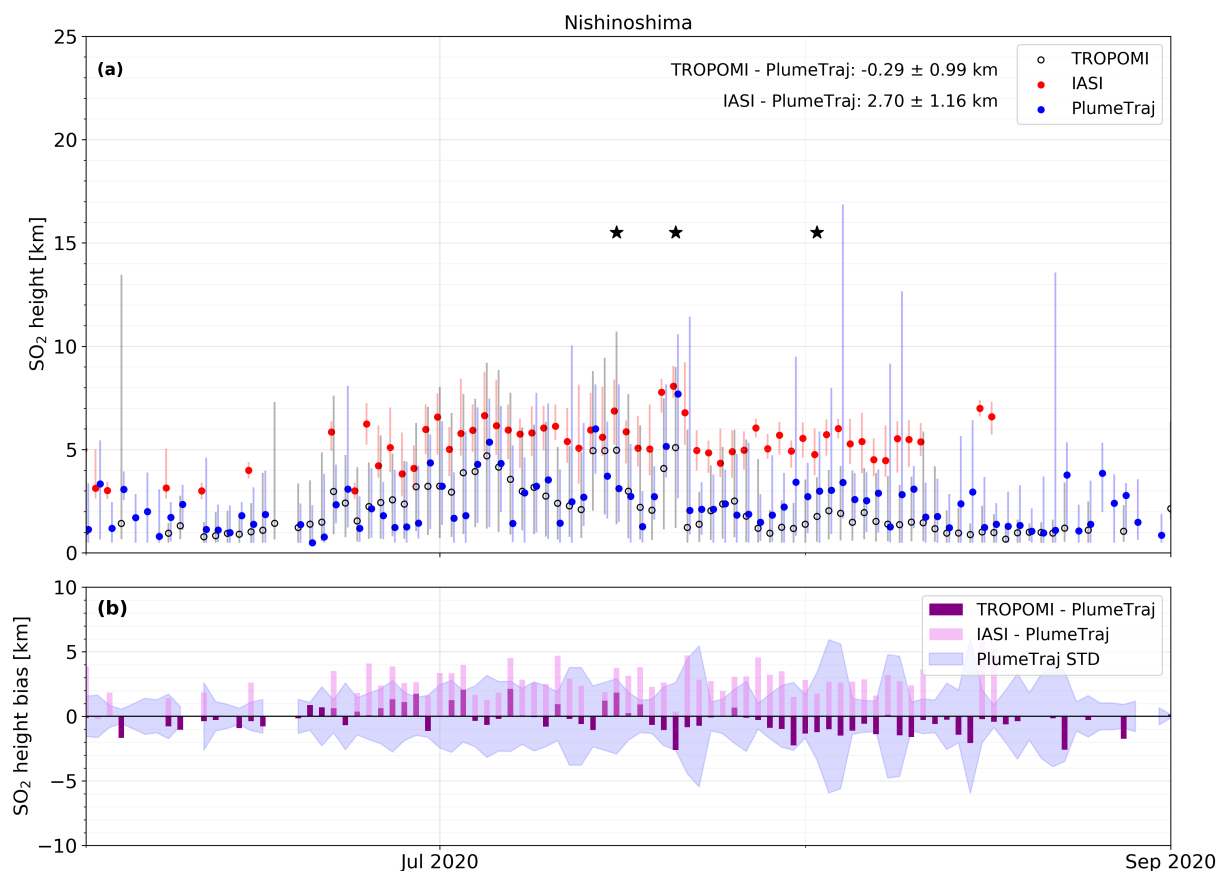


Figure 8. (a) Time series of daily SO₂ height from TROPOMI (black), IASI (red), and PlumeTraj (blue) for Nishinoshima during summer 2020. As in Figure 5, the dots correspond to the Q50 height estimates, while the error bars represent the Q10–Q90 ranges of the SO₂ mass profiles. The median SO₂ height difference $\pm$ standard deviation between TROPOMI and PlumeTraj, and between IASI and PlumeTraj, is also indicated. Stars mark the dates selected for the detailed analyses shown in Figure 9. (b) Daily differences in SO₂ height between TROPOMI and PlumeTraj (purple) and between IASI and PlumeTraj (violet), together with the daily PlumeTraj standard deviation (blue shaded area).

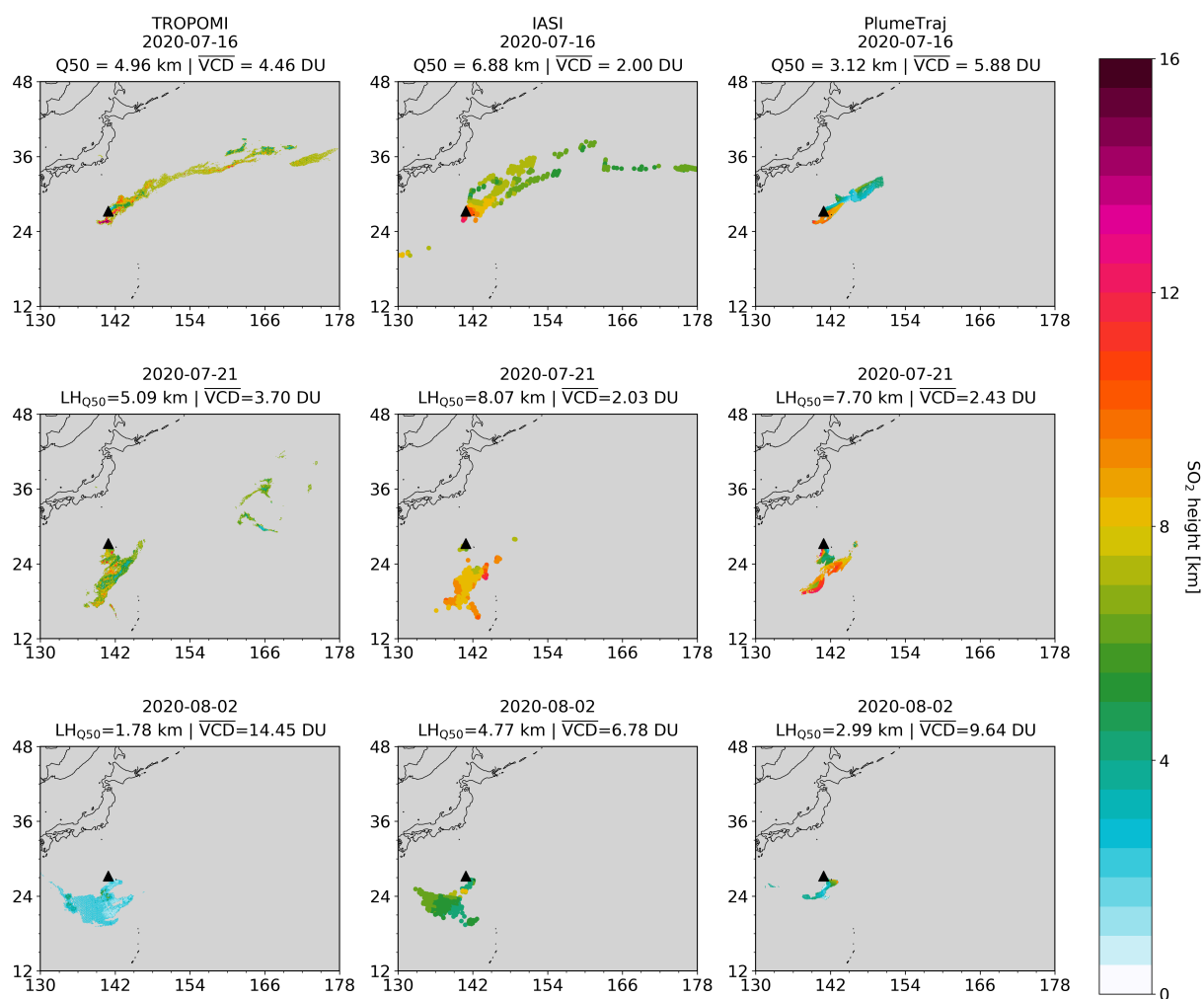


Figure 9. SO₂ height maps derived from TROPOMI, IASI, and PlumeTraj for the Nishinoshima eruption during summer 2020 on three representative days. For each day and dataset, the median SO₂ mass height (Q50) and mean VCD ($\overline{\text{VCD}}$) are indicated.



Another illustrative example is provided by Figure 10 for the eruption of Lewotolok, Indonesia, in November–December 2020 (Global Volcanism Program, 2021b). The event is characterised by relatively modest SO₂ loadings, with a mean TROPOMI VCD of 8.58 DU over the study period. In contrast to Nishinoshima, the overall TROPOMI bias relative to PlumeTraj is higher than that of IASI. However, the large scatter of PlumeTraj leads to different levels of agreement between the datasets depending
415 on the day.

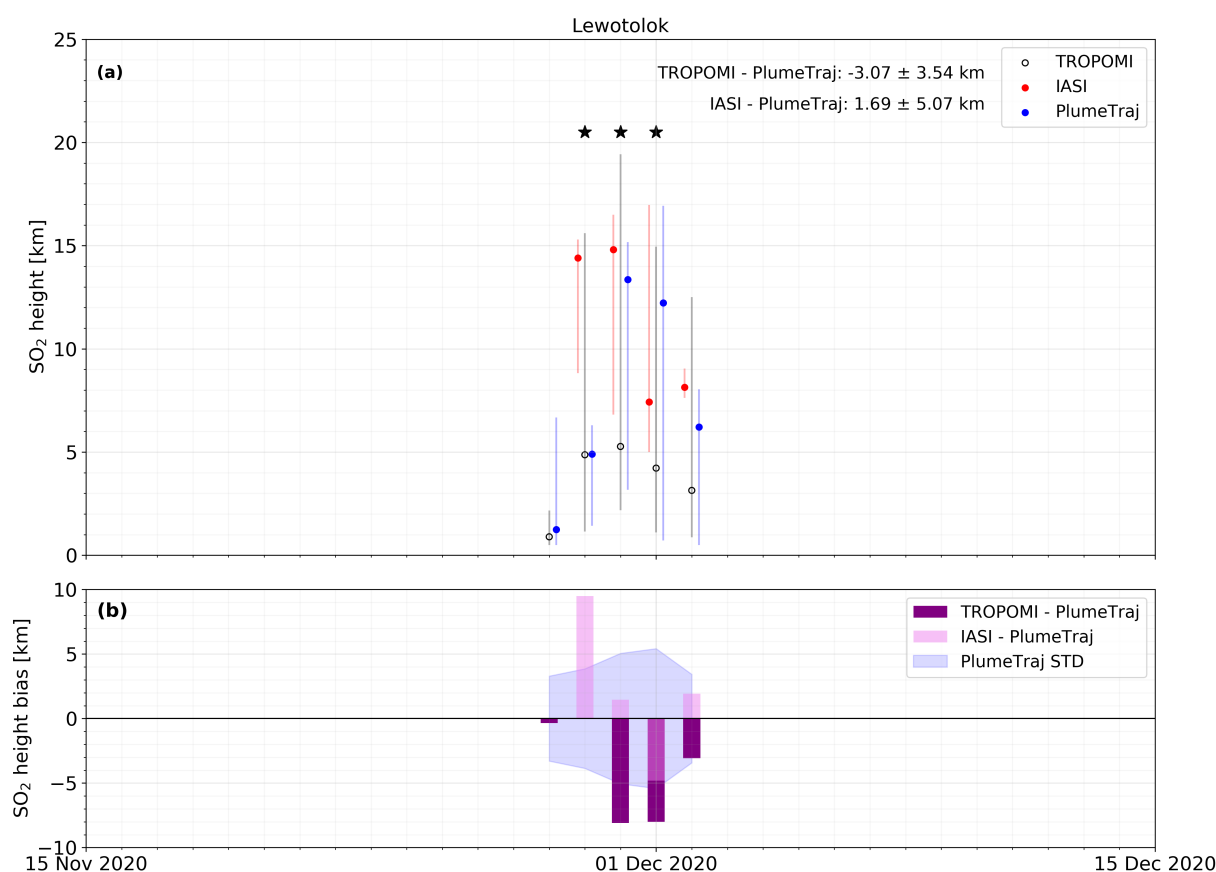


Figure 10. (a) Time series of daily SO₂ height from TROPOMI (black), IASI (red), and PlumeTraj (blue) for Lewotolok in November–December 2020. Symbols and annotations are defined as in Figure 8. (b) Differences in SO₂ height between TROPOMI and PlumeTraj (purple) and between IASI and PlumeTraj (violet), together with the daily PlumeTraj standard deviation (blue shaded area).

Figure 11 illustrates this variability and further highlights the complementary of the three datasets as a function of SO₂ plume altitude and column density. On 29 November 2020, although TROPOMI and PlumeTraj derive remarkably similar median SO₂ heights (4.87 and 4.90 km, respectively), TROPOMI reveals a more heterogeneous plume structure, with SO₂ altitudes up to 17 km not observed by PlumeTraj and a significantly larger mean VCD (53.4 DU compared to 33.2 DU for PlumeTraj). At the
420 same time, IASI does not detect the low-altitude plume close to the volcano and mainly retrieves elevated SO₂ located further downwind. In contrast, TROPOMI does not capture this UTLS SO₂ plume located south of the volcano, likely because the



weak SO₂ signal combined with the reduced sensitivity of UV retrievals in the UTLS increases the uncertainty of the retrieved SO₂ height. The most illustrative case is 30 November 2020, when TROPOMI shows the best agreement with PlumeTraj for low-altitude SO₂, whereas IASI aligns well with PlumeTraj for the plume fraction reaching the UTLS. This behaviour is consistent with the known strengths of UV and TIR observations, with UV retrievals generally providing higher sensitivity in the lower troposphere and TIR measurements becoming more effective at higher altitudes where water-vapour interference is reduced. The following day exhibits broadly similar SO₂ heights from TROPOMI and IASI despite some differences in spatial structure, which likely arises from the different overpass times of the instruments. In comparison, the significantly higher SO₂ plume altitudes inferred by PlumeTraj suggest that the model suffers from additional uncertainties related to the trajectory analysis, possibly associated with the complex plume geometry and wind-field representation. Overall, similarly to Nishinoshima, PlumeTraj provides intermediate SO₂ heights between the UV and TIR products, with the relative agreement depending strongly on SO₂ plume properties.

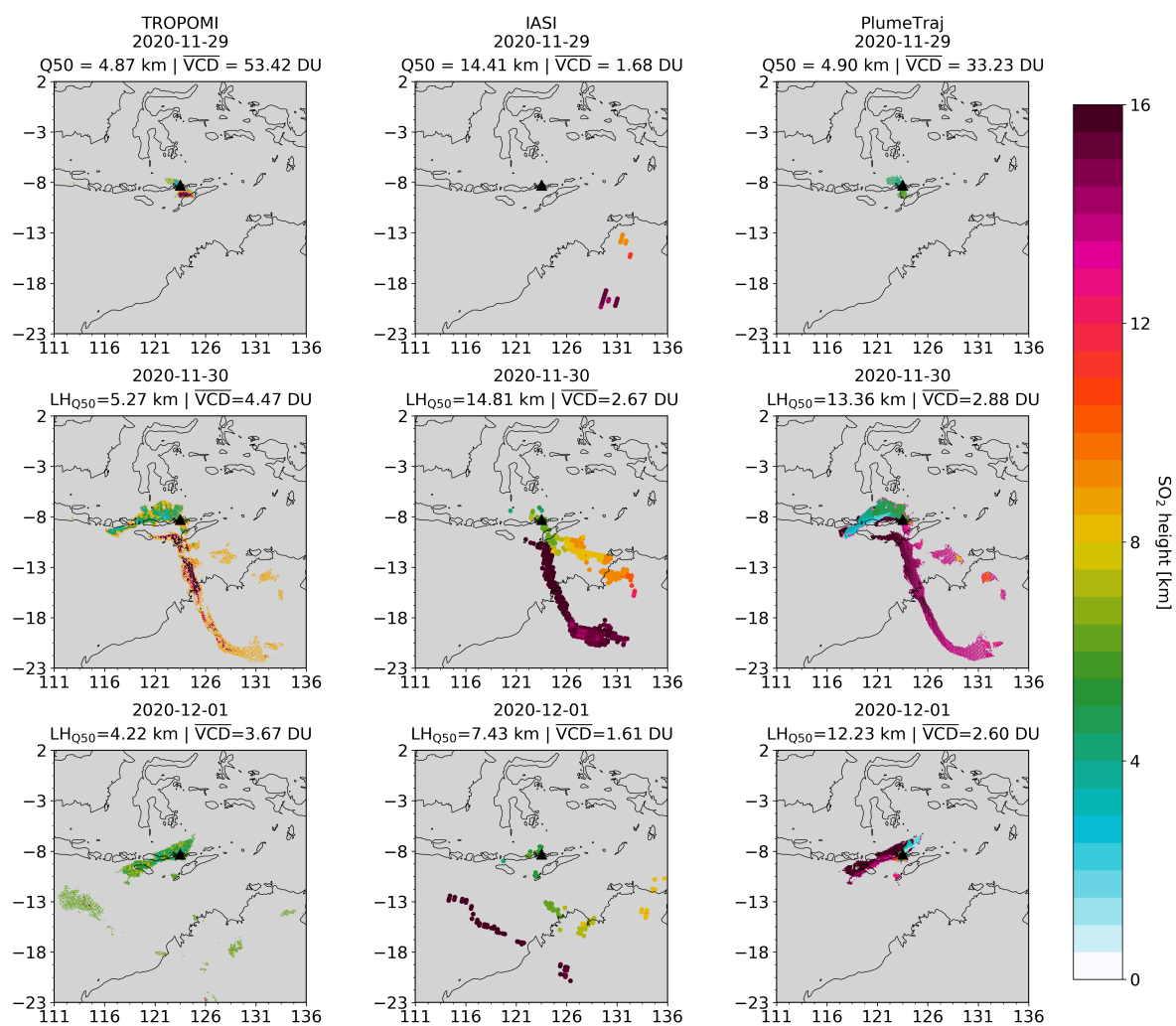


Figure 11. SO₂ height maps derived from TROPOMI, IASI, and PlumeTraj for the Lewotolok eruption in November–December 2020 on three representative days. For each day and dataset, the median SO₂ mass height (Q50) and mean VCD ($\overline{\text{VCD}}$) are indicated.



As a final example, Figure 12 shows the comparison for Nevado del Ruiz, a continuously degassing volcano in Colombia. Unlike the episodic eruptions discussed previously, Nevado del Ruiz emitted SO₂ persistently throughout 2020 (Lages et al., 2024), providing a large number of coincident observations over an extended period. For this case, TROPOMI and IASI retrieve relatively consistent SO₂ heights, generally between 4 and 6 km, and show a broadly similar overall behaviour. As a result, both TROPOMI and IASI display very weak correlations with PlumeTraj ($R = 0.16$ and 0.11 , respectively), despite relatively small median biases of 0.12 and 1.61 km. PlumeTraj shows a much larger variability, with most SO₂ height estimates at relatively low altitudes and some values reaching 17 km (see Figure B1). This behaviour is likely related to the wind conditions over this region, where winds at different altitudes often follow similar directions, limiting the ability of PlumeTraj to discriminate between plume altitudes and sometimes resulting in unrealistically high estimates and large associated uncertainties.

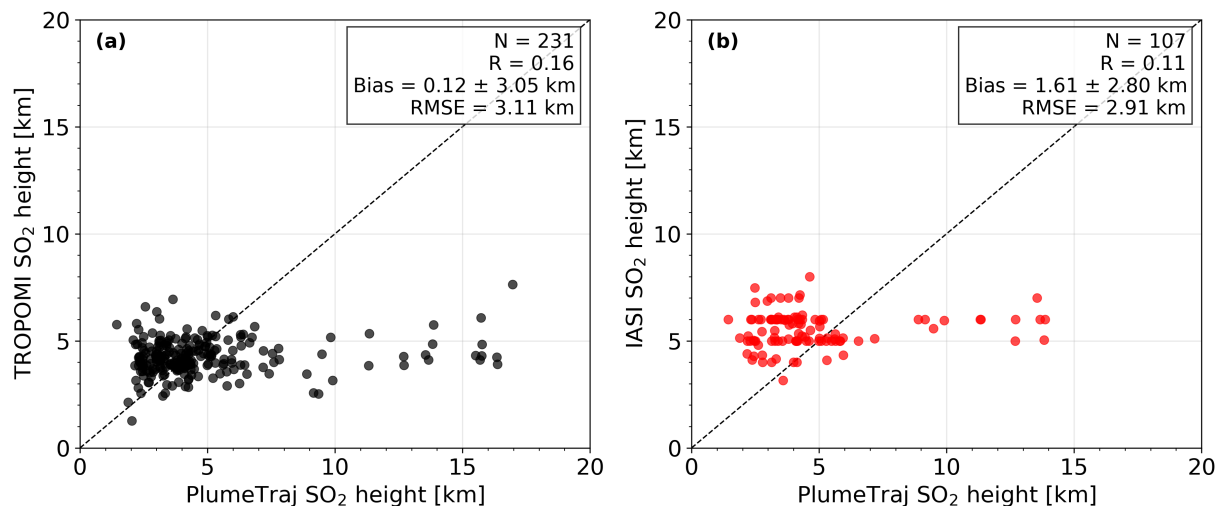


Figure 12. Comparison of median SO₂ heights derived from (a) TROPOMI and (b) IASI with PlumeTraj for Nevado del Ruiz during 2020. The dashed line indicates the one-to-one relationship. N denotes the number of coincident observations, R the correlation coefficient, Bias the median height difference relative to PlumeTraj, and RMSE the root-mean-square error.

To determine whether the findings from Nishinoshima, Lewotolok, and Nevado del Ruiz are representative of a broader range of volcanic conditions, we extended the analysis to a set of volcanic events in 2020, as well as to Kilauea (2018, 2020), La Soufrière (2021), Cumbre Vieja (2021), and Mauna Loa (2022). Figure 13 provides an overview of the comparisons between the three datasets. For most events, TROPOMI shows smaller biases relative to PlumeTraj than IASI, with median differences generally remaining within about 1 km, with three exceptions, Lewotolok, Sabancaya, and Popocatepetl, which exhibit a large scatter of the PlumeTraj results (because of limitations related to the winds). In contrast, IASI tends to retrieve systematically higher SO₂ heights, particularly for low- and mid-tropospheric plumes. Relatively large discrepancies are observed for several low- and mid-altitude plumes, such as Nishinoshima and Kilauea, for which TIR retrievals are expected to have reduced sensitivity. For higher-altitude plumes, the agreement between IASI and PlumeTraj tends to improve in some cases, as seen for Sabancaya, Popocatepetl, and Krakatau, although this behaviour is not systematic, as illustrated by La Soufrière. Overall,



Figure 13 indicates that PlumeTraj often provides intermediate SO_2 height estimates between the UV and TIR retrievals. Depending on SO_2 plume altitude and column density, PlumeTraj may therefore be more consistent with either TROPOMI or IASI, further suggesting the complementary nature of the three approaches.

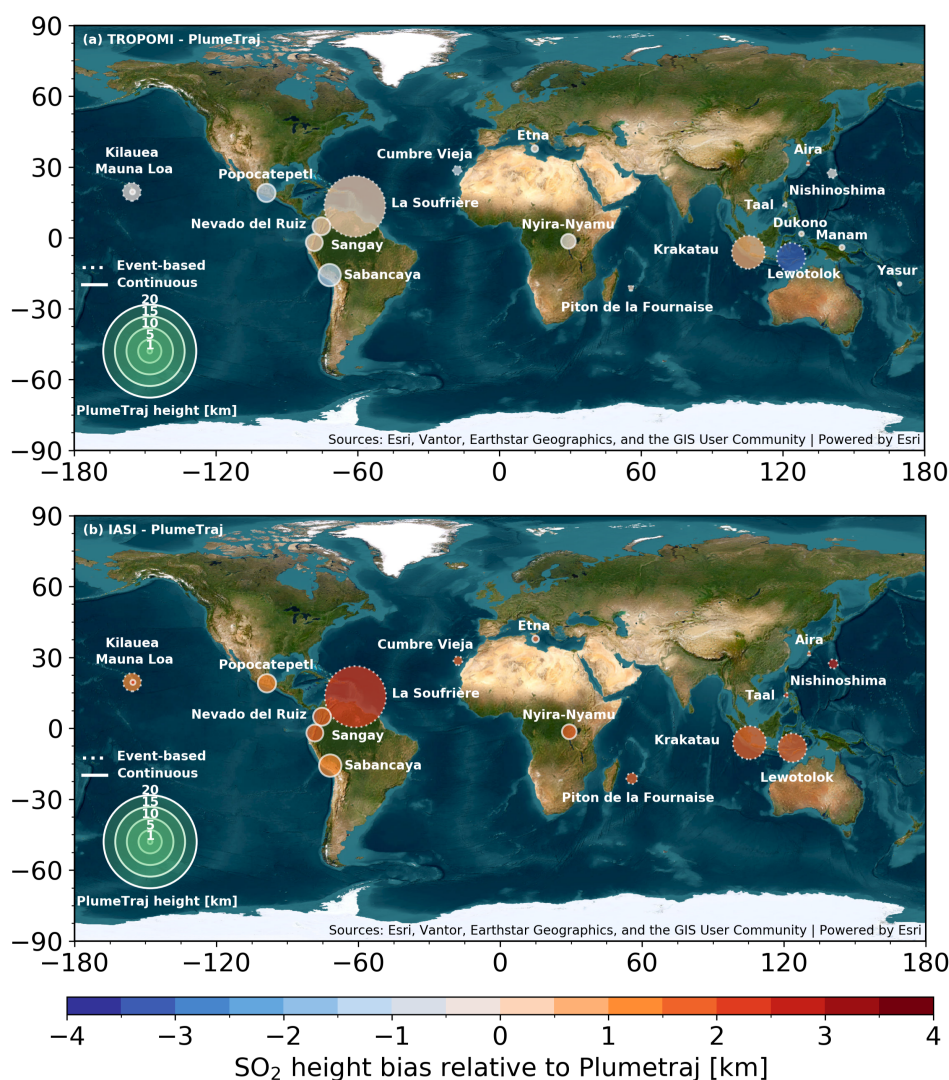


Figure 13. Comparison of SO_2 heights retrieved from (a) TROPOMI and (b) IASI, with respect to PlumeTraj for volcanic events in 2020, as well as for Kilauea (2018, 2020), La Soufrière (2021), Cumbre Vieja (2021), and Mauna Loa (2022). Circle size is proportional to the PlumeTraj median Q50 SO_2 height over the event, while colour indicates the median bias between TROPOMI/IASI and PlumeTraj. Outlines are solid or dotted depending on the event type. Map data from Esri World Imagery (2026).

455 In Figure 14, we compare the Q50 SO_2 heights from the three datasets. TROPOMI remains generally closer to the one-to-one relationship than IASI, particularly for low- and mid-altitude plumes, although some variability is still observed. In contrast,



IASI retrieves systematically higher Q50 heights than PlumeTraj for most events, confirming the tendency already identified in Figure 13. Similar conclusions are obtained for the Q90 heights (Figure B2). While the TROPOMI-PlumeTraj agreement remains globally unchanged, the agreement between IASI and PlumeTraj improves slightly for most events, consistent with the different vertical sensitivities of the UV and TIR measurements. Nevertheless, for plumes below approximately 6 km, IASI still tends to retrieve higher SO₂ heights than PlumeTraj, further supporting the positive low-altitude bias identified previously.

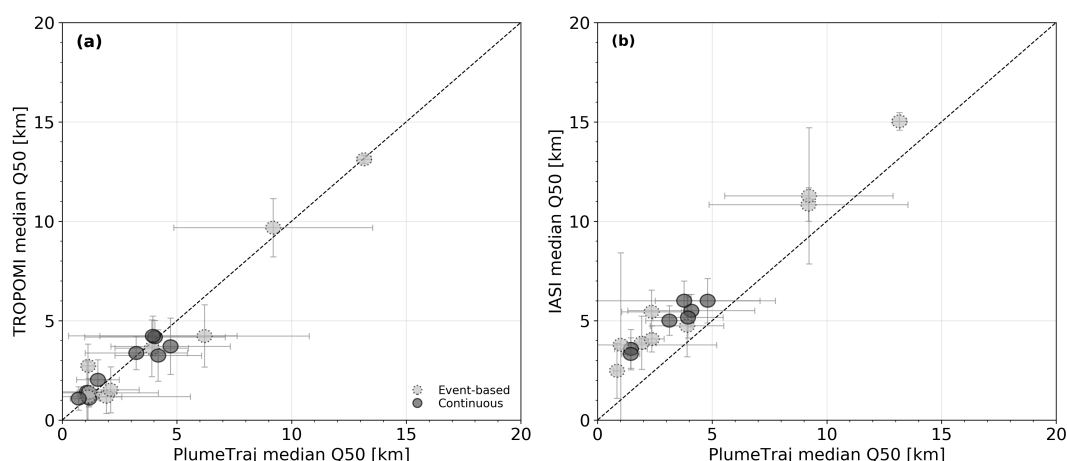


Figure 14. Comparison of median Q50 SO₂ heights derived from (a) TROPOMI and (b) IASI, with respect to PlumeTraj estimates for all volcanic events considered in this study. Marker styles distinguish event-based eruptions (dotted circles) from continuous emissions (solid circles). Vertical and horizontal error bars represent the standard deviations of the median SO₂ heights derived from the satellites and PlumeTraj datasets, respectively. The dashed line denotes the one-to-one relationship.



5 Conclusions

In this study, we presented the first long-term SO₂ plume-height dataset from UV nadir-viewing satellite observations, covering the complete TROPOMI record from 2018 to 2025. The product was generated using an improved LUT-COBRA approach applied to TROPOMI band 2, which exploits strong SO₂ absorption features in the short UV. As demonstrated in our recent study (Fabris et al., 2026), the algorithm shows high sensitivity, particularly for low SO₂ loadings and plumes located near the surface or in the UTLS. From the analysis of the global SO₂ data, we identified the major volcanic and anthropogenic SO₂ emissions over the studied period. We found that the SO₂ mass time series and the main SO₂ sources identified by TROPOMI are generally consistent with those reported in the recent IASI SO₂ height dataset of Clarisse et al. (2026). Our product captures a broad range of SO₂ emissions, from explosive volcanic eruptions such as Taal (2020), Mauna Loa (2022), and Ruang (2024), to persistent volcanic degassing at Popocatepetl, Sabancaya, and Etna, as well as anthropogenic sources including Baysun and Norilsk. These analyses demonstrate the capability of the product to monitor SO₂ emissions across a wide range of source types, plume altitudes, and atmospheric conditions. To assess the quality of the retrievals, the dataset was compared with independent SO₂ height retrievals from TIR observations by IASI. Because of the observation time difference between the two sensors, a direct comparison of TROPOMI and IASI is challenging. Instead, we compared time series of daily median SO₂ mass altitude over pre-defined regions. While this approach does not solve entirely sampling differences between the two datasets and likely hides comparison details, it is easily applicable to many volcanic sites. A broad comparison involving more than 40 volcanic events, including degassing and erupting volcanoes, revealed a general good consistency between the two datasets but an overall negative bias of TROPOMI relative to IASI varying from -0.7 to -12 km, in the worst case. These differences are discussed considering the fundamentally different vertical sensitivity of UV and TIR observations. TROPOMI exhibits improved sensitivity for low-altitude SO₂ plumes, whereas IASI becomes increasingly effective for plumes reaching the UTLS. To address this point, we repeated the comparison focusing on the upper part of the SO₂ mass profile, using the Q90 metric (the altitude leaving 90% of the SO₂ mass underneath) rather than the median SO₂ mass altitude. We showed that the agreement between TROPOMI and IASI improves significantly, suggesting that difference in vertical sensitivity is a main factor explaining the discrepancy between TROPOMI and IASI. For low plumes, the SO₂ heights from TROPOMI are still lower than IASI by about 1–2 km but is well within the combined uncertainty of TROPOMI and IASI height products. Despite the overall good agreement, the comparison also shows that for some volcanic eruptions like Lewotobi (2024) or Hunga Tonga (2021–2022), the accuracy of TROPOMI retrievals can be severely compromised by the presence of high aerosols loadings in the plume, leading to a negative bias of several kilometres.

Additional comparisons with height data independently retrieved with the PlumeTraj toolkit further support the robustness of the TROPOMI retrieved SO₂ heights. Case studies of Nishinoshima, Lewotolok, and Nevado del Ruiz illustrate both the strengths and limitations of the different approaches under contrasting volcanic and meteorological conditions. Overall, TROPOMI generally exhibits smaller biases relative to PlumeTraj than IASI for low plumes, with median differences often remaining within about 1 km. This is a promising result, and obtaining such a consistent SO₂ height retrieval from two completely different approaches suggests that both are performing well. Interestingly, the analyses show that PlumeTraj frequently



provides intermediate plume-height estimates between the UV and TIR products, with the agreement depending on SO₂ plume altitude, abundance, and the complexity of the atmospheric transport conditions. Together, these results highlight the strong complementarity of UV, TIR, and trajectory-based approaches for monitoring volcanic SO₂ emissions.

The long-term TROPOMI record presented here extends state-of-the-art satellite SO₂ plume-height observations to relatively weak and low-altitude emissions, including persistent volcanic degassing and anthropogenic emissions, for which SO₂ height information has so far been limited. This is particularly relevant for constraining SO₂ mass and flux estimates and investigating volcanic activity over long time series. Overall, this study shows that combining the sensitivity of TROPOMI to lower-altitude SO₂ with the complementary information provided by IASI and PlumeTraj allows a more comprehensive characterisation of the vertical distribution of volcanic SO₂, with important implications for our understanding of SO₂ transport, atmospheric lifetime, sulfate aerosol formation, and the climatic impacts of volcanic emissions.

Further work should focus on the following aspects.

- Further improving UV SO₂ height retrievals under high aerosol loading conditions. Aerosols remain one of the main sources of uncertainty in UV SO₂ height retrievals. Synthetic sensitivity analyses are currently being performed to better quantify their impact on the retrieved SO₂ plume heights. Including aerosol contributions within the LUT-COBRA framework therefore remains an important long-term objective.
- Further validating the TROPOMI SO₂ height dataset against independent plume-height observations. Comparisons with dedicated spaceborne lidar measurements, such as CALIOP and ATLID/EarthCARE, would provide an independent reference to further assess the robustness of the TROPOMI retrievals and evaluate the PlumeTraj height estimates.
- Extending the LUT-COBRA approach to future satellite missions and exploiting UV–TIR synergies. The Sentinel-4 and Sentinel-5 UVN instruments will extend the TROPOMI time series and provide additional information (e.g., hourly resolution data for Sentinel-4). In addition, having Sentinel-5 UVN and IASI-NG on the same platform (Metop-SG, launched in summer 2025) will provide new opportunities to further investigate the differences between UV and TIR SO₂ height retrievals. This could support the development of a synergistic SO₂ height product combining information from UV, TIR, and trajectory-based approaches, potentially providing more robust plume-height estimates over a wider range of SO₂ plume altitudes, abundances, and atmospheric conditions.
- PlumeTraj itself could benefit from the use of TROPOMI SO₂ height data in cases of low vertical wind shear. Indeed, we found that PlumeTraj occasionally returns unphysical plume heights when trajectories at multiple heights are equally possible. TROPOMI SO₂ heights could therefore provide an additional constraint to help select the correct trajectory solution. Furthermore, applying PlumeTraj to IASI observations would provide an interesting complementary analysis. Although PlumeTraj is independent regarding plume-height retrieval, it is not fully independent from TROPOMI because it is initialised using TROPOMI SO₂ detections. Initialising PlumeTraj with IASI data instead could potentially improve the agreement between IASI and PlumeTraj, as only the pixels to which IASI is sensitive would be considered.



Appendix A: Case study overview

Table A1 provides an overview of the volcanic SO₂ sources considered in this study, including their locations and summit elevations.

Table A1. Overview of the volcanic SO₂ sources considered in this study, including ID, location, and summit elevation.

ID	Source	Country	Coordinates	Summit [km]
0	Aira	Japan	31.577 °N, 130.659 °E	1.117
1	Ambae	Vanuatu	15.389 °S, 167.835 °E	1.496
2	Ambrym	Vanuatu	16.250 °S, 168.120 °E	1.334
3	Cumbre Vieja	Spain	28.570 °N, 17.830 °W	2.426
4	Dukono	Indonesia	1.699 °N, 127.878 °E	1.273
5	Etna	Italy	37.748 °N, 14.999 °E	3.357
6	Fagradalsfjall	Iceland	63.895 °N, 22.258 °W	0.250
7	Fernandina	Ecuador	0.370 °S, 91.550 °W	1.476
8	Hayli Gubbi	Ethiopia	13.511 °N, 40.716 °E	0.493
9	Hunga Tonga	Tonga	20.553 °S, 175.384 °W	0.114
10	Kanlaon	Philippines	10.410 °N, 123.130 °E	2.422
11	Karymsky	Russia	54.049 °N, 159.443 °E	1.513
12	Kilauea	USA	19.421 °N, 155.287 °W	1.222
13	Klyuchevskoy	Russia	56.056 °N, 160.642 °E	4.754
14	Krakatau	Indonesia	6.101 °S, 105.423 °E	0.285
15	Krashenninnikov	Russia	54.596 °N, 160.270 °E	1.816
16	Kronotsky	Russia	54.753 °N, 160.533 °E	3.482
17	La Soufrière	Saint Vincent and the Grenadines	13.330 °N, 61.180 °W	1.220
18	Lewotobi	Indonesia	8.542 °S, 122.775 °E	1.703
19	Lewotolok	Indonesia	8.274 °S, 123.508 °E	1.431
20	Manam	Papua New Guinea	4.080 °S, 145.037 °E	1.807
21	Mauna Loa	USA	19.475 °N, 155.608 °W	4.170
22	Nevado del Ruiz	Colombia	4.892 °N, 75.324 °W	5.279
23	Nishinoshima	Japan	27.247 °N, 140.874 °E	0.100
24	Nyira-Nyamu	DR Congo	1.464 °S, 29.225 °E	3.264
25	Piton de la Fourmaise	France	21.244 °S, 55.708 °E	2.632
26	Popocatepetl	Mexico	19.023 °N, 98.622 °W	5.393
27	Raikoke	Russia	48.292 °N, 153.250 °E	0.551
28	Reykjanes	Iceland	63.817 °N, 22.717 °W	0.140
29	Ruang	Indonesia	2.306 °N, 125.367 °E	0.703
30	Sabancaya	Peru	15.787 °S, 71.857 °W	5.960
31	Sangay	Ecuador	2.005 °S, 78.341 °W	5.286
32	Sheveluch	Russia	56.653 °N, 161.360 °E	3.283
33	Shishaldin	USA	54.756 °N, 163.970 °W	2.857
34	Sierra Negra	Ecuador	0.830 °S, 91.170 °W	1.124
35	Taal	Philippines	14.011 °N, 120.998 °E	0.311
36	Ubinas	Peru	16.345 °S, 70.897 °W	5.608
37	Ulawun	Papua New Guinea	5.050 °S, 151.330 °E	2.334
38	Yasur	Vanuatu	19.532 °S, 169.447 °E	0.361

To compare the TROPOMI BD2 product with IASI observations and PlumeTraj estimates, spatial domains and analysis periods were defined for each volcanic source. These settings are summarised in Table A2, while the corresponding spatial



domains are shown in Figure A1. The detailed results presented in Section 4 are provided in the Supplementary Material. Note that NaN values in the Supplementary Material indicate either that one of the datasets did not detect any SO₂ over the analysed period and volcanic region, or that no coincident observation days were available between the datasets.

Table A2. Spatial domains, temporal coverage, and event classification of SO₂ sources.

ID	Source	Longitude limits	Latitude limits	Dates	Event type
0	Aira	122.0–142.0 °E	20.0–40.0 °N	25 Jan–05 Feb 2020	1
1	Ambae	155.0 °E–125.0 °W	34.0 °S–11.0 °N	15 Jul–15 Aug 2018	1
2	Ambrym	155.0 °E–125.0 °W	34.0 °S–11.0 °N	01 Oct–31 Dec 2018	2
3	Cumbre Vieja	28.0–8.0 °W	19.5–35.5 °N	19 Sep–14 Dec 2021	1
4	Dukono	122.5°E–132.5°E	3.5°S–6.5°N	01 Jan–31 Dec 2020	2
5	Etna	6.0°E–27.0°E	26.0°N–47.0°N	01 May 2018–31 Dec 2025	2
6	Fagradalsfjall	35.0°W–5.0°W	55.0°N–75.0°N	25 Apr–25 May 2021	1
7	Fernandina	99.0°W–84.0°W	7.0°S–5.0°N	01 Mar–01 Apr 2024	1
8	Hayli Gubbi	28.0°E–68.0°E	4.5°N–28.5°N	22 Nov–01 Dec 2025	1
9	Hunga Tonga	150.0°E–150.0°W	35.0–5.0°S	18–31 Dec 2021	1
				12–26 Jan 2022	1
10	Kanlaon	112.0–130.0°E	1.5–17.5°N	12–17 May 2025	1
11	Karymsky	140.0°E–148.0°W	36.0–72.0°N	01 Apr–01 May 2022	1
12	Kilauea	163.0°E–125.0°W	3.0–39.0°N	01 May–05 Aug 2018	2
				20–31 Dec 2020	1
				15 Nov–31 Dec 2025	1
13	Klyuchevskoy	140.0°E–148.0°W	36.0–72.0°N	30 Oct–05 Nov 2023	1
				25 Jul–20 Aug 2025	1
14	Krakatau	89.5–117.5°E	21.5°S–6.5°N	22–31 Dec 2018	1
				10–15 Apr 2020	1
15	Krashennnikov	140.0°E–148.0°W	36.0–72.0°N	25 Jul–20 Aug 2025	1
16	Kronotsky	140.0°E–148.0°W	36.0–72.0°N	01–25 Oct 2025	1
17	La Soufrière	84.0–20.0°W	8.0°S–28.0°N	09–15 Apr 2021	1
18	Lewotobi	111.0–136.0°E	23.0°S–2.0°N	01 Nov–08 Dec 2024	1
				19–23 Mar 2025	1
				10–25 Jun 2025	1
19	Lewotolok	111.0–136.0 °E	23.0 °S–2.0 °N	28 Nov–02 Dec 2020	1

Longitude and latitude limits represent the spatial domain of each source. Date ranges correspond to individual SO₂ emission periods. Event types are defined as 1 = event-based emission and 2 = continuous emission.



Table A2. Continued.

ID	Source	Longitude limits	Latitude limits	Date range	Event type
20	Manam	134.0–154.0 °E	9.0 °S–3.0 °N	01 Jan–01 Feb 2019	1
				01 Jan–31 Dec 2020	2
21	Mauna Loa	163.0 °E–125.0 °W	3.0–39.0 °N	28 Nov–10 Dec 2022	1
22	Nevado del Ruiz	83.0–71.0 °W	0.0–10.0 °N	01 Jan–31 Dec 2020	2
23	Nishinoshima	114.5–178.5 °E	12.0–48.0 °N	01 Jun–01 Sep 2020	1
24	Nyira-Nyamu	17.0–35.0 °E	6.0 °S–4.0 °N	01 Jan–31 Dec 2020	2
				01 Jun–31 Dec 2024	2
				01 Jan–01 May 2025	2
25	Piton de la Fournaise	48.0–63.0 °E	27.0–15.0 °S	05–20 Feb 2020	1
				01–10 Apr 2020	1
				01–15 Dec 2020	1
26	Popocatepetl	106.0–91.0 °W	15.0–25.0 °N	01 Jan–31 Dec 2020	2
				15 Oct–15 Nov 2024	1
27	Raikoke	150.0 °E–160.0 °W	38.0–68.0 °N	20 Jun–01 Jul 2019	1
28	Reykjanes	35.0–5.0 °W	55.0–75.0 °N	16 Mar–08 May 2024	1
				29 May–22 Jun 2024	1
				22 Aug–06 Sep 2024	1
				16 Jul–05 Aug 2025	1
29	Ruang	84.5–134.5 °E	7.0 °S–18.0 °N	15 Apr–05 May 2024	1
30	Sabancaya	81.0–61.0 °W	23.0–11.0 °S	15 Aug–31 Dec 2018	2
				01 Jan–31 Dec 2020	2
				01 Jan–31 Dec 2022	2
31	Sangay	86.0–74.0 °W	6.0 °S–2.0 °N	01 Jan–31 Dec 2020	2
				01 Mar–01 Apr 2021	1
32	Sheveluch	140.0 °E–148.0 °W	36.0–72.0 °N	15 Aug–15 Sep 2019	1
				01 Apr–01 May 2023	1
				01 Aug–01 Oct 2024	1
33	Shishaldin	172.0–152.0 °W	49.0–61.0 °N	10 Jul–05 Nov 2023	2
34	Sierra Negra	99.0–84.0 °W	7.0 °S–5.0 °N	25 Jun–25 Aug 2018	1
35	Taal	106.0–142.0 °E	0.0–35.0 °N	12–22 Jan 2020	1
36	Ubinas	81.0–61.0 °W	23.0–11.0 °S	01 Jul–01 Aug 2019	2
37	Ulawun	134.0–164.0 °E	14.0 °S–10.0 °N	25 Jun–01 Sep 2019	2
				20–26 Nov 2023	1
38	Yasur	158.0–178.0 °E	27.0–11.0 °S	01 Jan–31 Dec 2020	2

Longitude and latitude limits represent the spatial domain of each source. Date ranges correspond to individual SO₂ emission periods. Event types are defined as 1 = event-based emission and 2 = continuous emission.

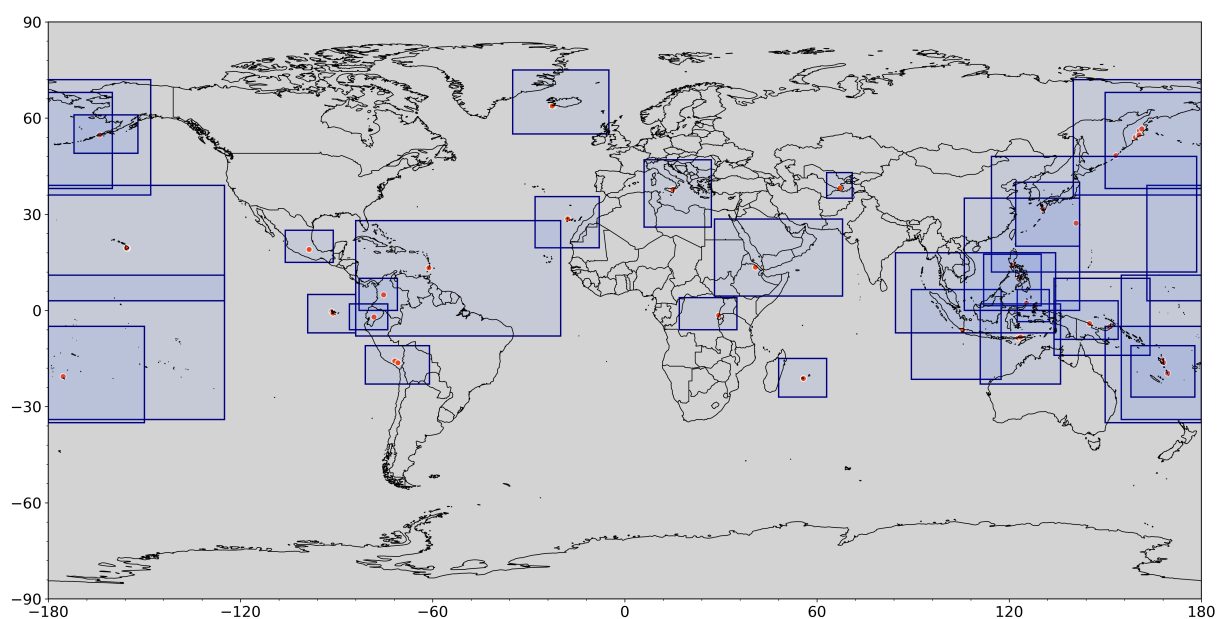


Figure A1. Location (red dots) and spatial domains (blue shaded areas) of each SO₂ source considered in this study (see Tables A1 and A2).



Appendix B: Dataset comparison

Figure B1 shows the comparison of daily SO₂ heights derived from TROPOMI, IASI, and PlumeTraj for Nevado del Ruiz in 2020, in complement of the results from Section 4.

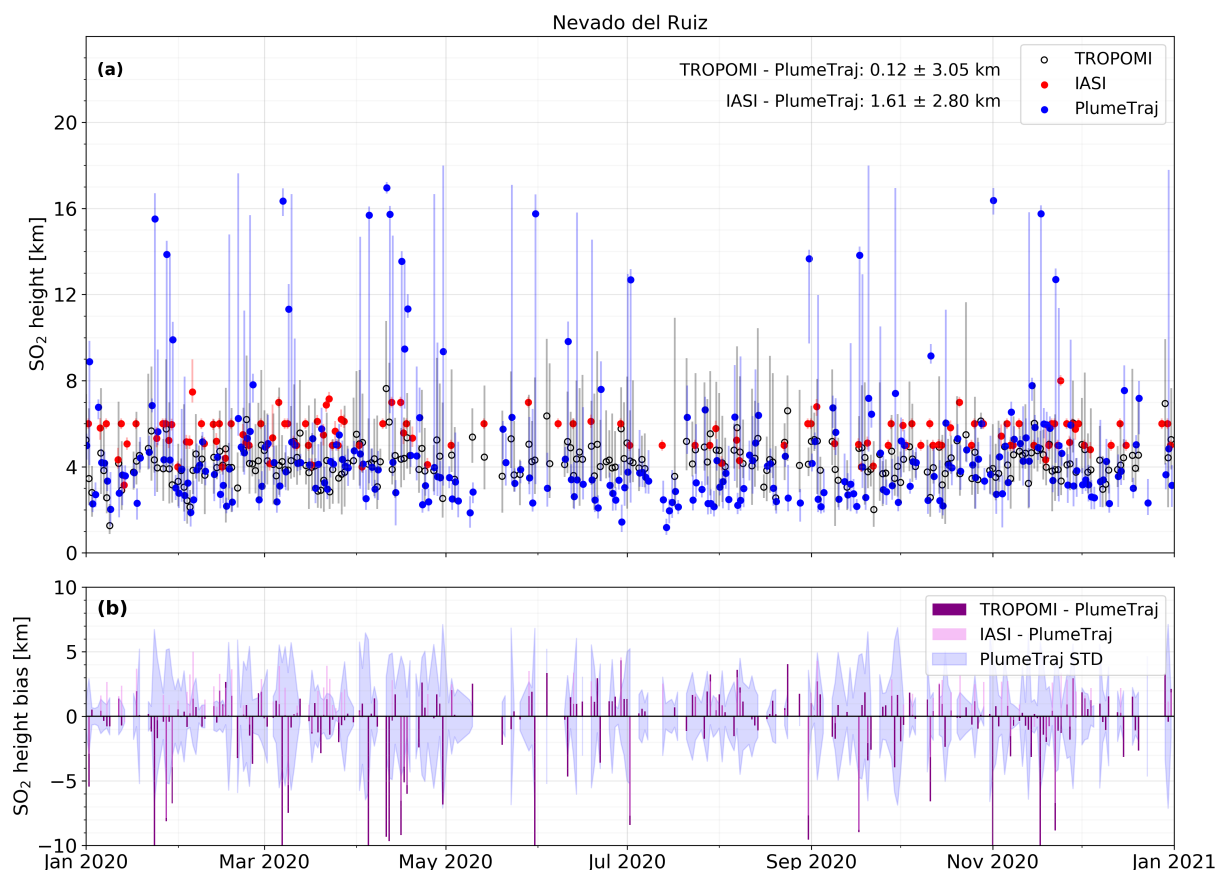


Figure B1. (a) Time series of daily SO₂ height from TROPOMI (black), IASI (red), and PlumeTraj (blue) for Nevado del Ruiz in 2020. Dots and error bars are defined as in Figure 8. The median SO₂ height difference $\pm$ standard deviation between TROPOMI and PlumeTraj, and between IASI and PlumeTraj, is indicated. (b) Daily differences in SO₂ height between TROPOMI and PlumeTraj (purple) and between IASI and PlumeTraj (violet), together with the daily PlumeTraj standard deviation (blue shaded area).

Figure B2 compares the Q90 SO₂ heights derived from the three datasets for all volcanic events, complementing Figure 14 presented in Section 4.

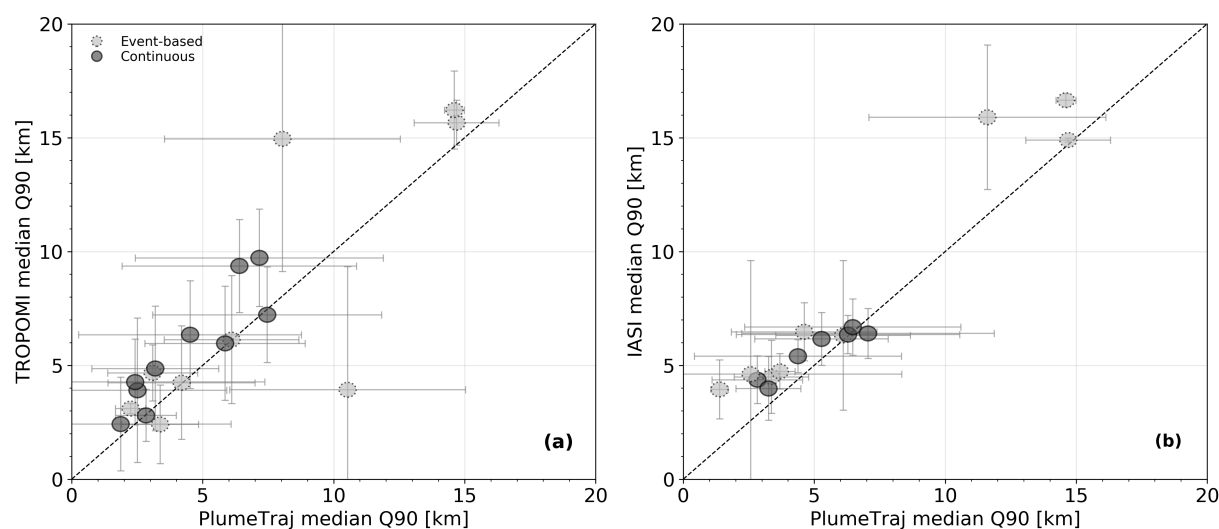


Figure B2. Comparison of median Q90 SO₂ heights derived from (a) TROPOMI and (b) IASI, with respect to PlumeTraj estimates for all volcanic events considered in this study. Marker styles distinguish event-based eruptions (dotted circles) from continuous emissions (solid circles). Vertical and horizontal error bars represent the standard deviations of the median SO₂ heights derived from the satellites and PlumeTraj datasets, respectively. The dashed line denotes the one-to-one relationship.



Data availability. Additional comparison results supporting the analyses presented in Section 4 are given in the Supplementary Material. The full-mission TROPOMI BD2 SO₂ plume-height dataset is freely available from the main author upon request (the dataset will be distributed on a dedicated repository once the paper is accepted). The IASI product is available from the AERIS data server (<https://iasi.aeris-data.fr>), while the PlumeTraj data can currently be obtained upon request from Mike Burton and Benjamin Esse and will be publicly released through a Figshare repository (<https://doi.org/10.48420/31267816>) upon publication of the associated study (Esse et al., in prep).

Author contributions. Lorenzo Fabris developed BD2 LUT-COBRA, processed the complete TROPOMI timeframe, produced the long-term SO₂ plume-height dataset, and analysed the results through comparisons with the IASI and PlumeTraj datasets. He prepared the manuscript and figures with contributions from all co-authors. Nicolas Theys supervised the research, advised on the selection of case studies, and supported the interpretation of the results. Lieven Clarisse and Bruno Franco provided the IASI dataset and contributed to its analysis, while Mike Burton and Benjamin Esse shared their PlumeTraj dataset and helped interpreting the results. Jonas Vlietinck contributed to the optimisation of the processing scripts and to the refinement of the Level-2 product format. Huan Yu, Hugues Brenot, Thomas Danckaert, and Michel Van Roozendaal offered constructive comments on the study. All co-authors contributed to the revision of the manuscript.

Competing interests. At least one of the (co-)authors is a member of the editorial board of Atmospheric Chemistry and Physics.

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