



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

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Abstract. Over the past decades, satellite measurements of atmospheric sulphur dioxide (SO₂) have served a wide range of applications, from volcanology to air quality monitoring and climate assessment. In this paper, we present a 2007–2025 record of twice-daily global SO₂ vertical column abundances and SO₂ plume altitudes derived from measurements by the three Infrared Atmospheric Sounding Interferometer (IASI) instruments onboard the Metop platforms. Building upon earlier work, the algorithm has been refined and complemented with several new components. Most notably, the sensitivity of the algorithm to low SO₂ abundances and low-altitude plumes has been improved and the plume altitude retrieval now features enhanced performance for large SO₂ columns. Special care was taken to maximize consistency of the product over time and across the IASI instruments. In addition to SO₂ at the retrieved altitude, the dataset also includes SO₂ column retrievals assuming plume altitudes ranging from 1 to 60 km. These allow the construction of averaging kernels that can be used in model assimilation or to obtain more accurate column estimates when the plume altitude is constrained by independent information. The first part of the paper details the retrieval methodology and presents sensitivity and uncertainty analyses. The latter indicate that the retrieval uncertainty is smallest for plumes above 8 km and increases gradually toward lower altitudes, particularly within the first few kilometres and in atmospheres with a high water vapour content. Detailed comparisons with measurements from the CALIOP lidar indicate that plume altitudes are generally accurate to within 1–2 km. Column comparisons with TROPOMI in fresh volcanic plumes indicate reasonable agreement. In the second part of the paper, we present an overview of the 18-year dataset, providing detailed time series of SO₂ column abundances and mass-altitude profiles, with a focus on volcanic SO₂. For each eruption with a plume mass exceeding 30 kt, we report the maximum atmospheric SO₂ mass, the mass below and above 8 km altitude, the peak plume altitude, and the altitude range containing 75% of the mass. When available, the maximum mass is compared with estimates reported in the literature. The SO₂ altitude and column data from IASI/Metop-A, -B, and -C are available at <https://dx.doi.org/10.25326/870> (Clarisse and Franco, 2026a), <https://dx.doi.org/10.25326/869> (Clarisse and Franco, 2026b), and <https://dx.doi.org/10.25326/868> (Clarisse and Franco, 2026c), respectively.



1 Introduction

Atmospheric sulphur dioxide (SO_2) is a key pollutant released by human activities and volcanoes, with annual emissions respectively on the order of 60–100 Tg (Guizzardi et al., 2025) and 13–30 Tg (Fischer et al., 2019; Fioletov et al., 2023). It contributes to the formation of fine particulate matter and sulphuric acid aerosols, affecting air quality, human health, and the Earth’s radiative balance (Lelieveld et al., 2015; Kremser et al., 2016). Dry and wet deposition of SO_2 cause acidification of soil and surface water, with harmful effects on plants, aquatic life, and soil microorganisms (Fowler et al., 2009).

For several decades, global SO_2 total column abundances (and more recently plume heights) have been routinely measured by nadir-viewing high-resolution spectrometers onboard satellites. The most commonly used long-term SO_2 datasets are derived from ultraviolet (UV) measurements by OMI (Yang et al., 2007; Fioletov et al., 2013), 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 SO_2 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 (e.g., Surono et al., 2012; Brenot et al., 2021), investigations of volcanic plume dispersion and dynamics (e.g., Prata et al., 2017; Khaykin et al., 2022), assimilation into atmospheric transport models to improve forecasting (e.g., Boichu et al., 2014; Inness et al., 2022; Bacles et al., 2025), climate studies (e.g., Haywood et al., 2010; Malavelle et al., 2017), data-driven quantification of volcanic emissions and anthropogenic point sources (e.g., Theys et al., 2013; Carboni et al., 2019; Fioletov et al., 2023), estimation of SO_2 atmospheric lifetimes (e.g., Beirle et al., 2014; Fioletov et al., 2015), derivation of vertical emission profiles of eruptions through model inversion (e.g., Eckhardt et al., 2008; Sadeghi et al., 2025), and estimation of regional and global top-down emissions through model assimilation (e.g., Wang et al., 2020; Qu et al., 2022).

IASI, short for Infrared Atmospheric Sounding Interferometer, is the hyperspectral infrared sounder onboard the polar-orbiting European Metop satellite series. IASI measures the outgoing infrared radiation between 645 and 2760 cm^{-1} at a resolution of 0.5 cm^{-1} . It provides global coverage twice daily, with equatorial morning and evening overpasses at 09:30 and 21:30 local solar time and a circular ground footprint of 12 km at nadir. The first IASI instrument was launched onboard Metop-A in October 2006 (Clerbaux et al., 2009), followed by the launch of Metop-B in September 2012 and Metop-C in November 2018. IASI/Metop-A was decommissioned in late 2021, while the other two instruments are still fully operational. Together, the three IASI instruments provide a uniquely consistent measurement record spanning more than 18 years.

In this paper, we present a reanalysed SO_2 total column and plume height dataset derived from IASI observations covering the period 2007–2025. The algorithm builds upon earlier retrieval schemes (Clarisse et al., 2012, 2014) with improved performance in retrieving altitudes of fresh SO_2 plumes and in quantifying low SO_2 abundances and low-altitude plumes. In addition, significant effort was made to ensure that the product is fully consistent in time and across the different IASI instruments. For each IASI observation, the dataset also provides SO_2 total column estimates for assumed altitudes ranging from 1 to 60 km. These can be used to obtain a total column estimate corresponding to an SO_2 altitude or an SO_2 altitude profile derived from an independent source (i.e., model or other measurement).



In the next section (Sect. 2), we present the plume altitude retrieval and illustrate it with a series of volcanic plumes. Comparisons are made with altitudes derived from the CALIOP lidar. Section 3 details the algorithm used for the derivation of SO₂ total columns. Here, comparisons are presented with SO₂ abundances retrieved from TROPOMI. In Sect. 3.4, we discuss retrieval uncertainties. The remainder of the paper is dedicated to the presentation and analysis of the 18-year dataset (Sect. 4). This includes an overview of the twice-daily total retrieved masses and vertical profiles, and a detailed catalogue of the maximum masses observed for all major volcanic eruptions since July 2007.

2 Altitude retrieval

SO₂ plumes, whether emitted by volcanoes or anthropogenically, are typically confined to a relatively narrow vertical layer less than a few kilometres thick. The layer height at which SO₂ peaks is a useful quantity on its own, but it is also a key input parameter for total column retrievals. Measurements from high-resolution UV (Yang et al., 2010; Hedelt et al., 2019; Fedkin et al., 2021; Theys et al., 2022) and IR spectrometers (Clerbaux et al., 2008; Carboni et al., 2012; Clarisse et al., 2014; Carboni et al., 2016) can both be used to derive information about the SO₂ layer height. In this section, we present two complementary methods for retrieving the layer height from IASI observations. The first method serves a dual purpose: identifying those observations with detectable quantities of SO₂ and retrieving the plume height. The second method is used to constrain the height of saturated plumes.

2.1 Hyperspectral range index method

The hyperspectral range index (HRI) or matched filter method is a widely adopted technique for the detection of weakly absorbing species (Walker et al., 2011; Manolakis et al., 2016; Noppen et al., 2025). It assigns to each observed spectrum $\mathbf{y}$ a value

$$\text{HRI}(\mathbf{y}) = \frac{\mathbf{K}^T \mathbf{S}^{-1} (\mathbf{y} - \bar{\mathbf{y}})}{\sqrt{\mathbf{K}^T \mathbf{S}^{-1} \mathbf{K}}}, \quad (1)$$

with $\bar{\mathbf{y}}$ and $\mathbf{S}$ the mean spectrum and covariance matrix of a representative set of spectra containing only background concentrations of the species of interest (in this case, SO₂). The vector $\mathbf{K} = \Delta \mathbf{y} / \Delta \text{SO}_2$ is a Jacobian with respect to a variation in the total column of SO₂ (typically a small amount, such as 5 DU, where DU stands for Dobson Unit and equals 2.69×10^{16} molec cm⁻²). The HRI, as a weighted projection of the observed spectrum onto this Jacobian, quantitatively expresses the presence of the spectral signature $\mathbf{K}$ in the observed spectrum. On the set of spectra from which $\bar{\mathbf{y}}$ and $\mathbf{S}$ were calculated, the HRI follows approximately a Gaussian distribution with a mean of zero and a standard deviation of one. For this reason, its value can be interpreted in probabilistic terms, e.g., a value above 5 occurs in less than 0.00003% of the background spectra; a spectrum with an HRI of 5 is therefore expected to contain the spectral signature of SO₂.

Focusing on the ν_3 absorption band of SO₂ between 1310 and 1400 cm⁻¹, it was shown in Clarisse et al. (2014) that the SO₂ Jacobians $\mathbf{K}_h$, calculated with respect to SO₂ variations at a given altitude h , depend largely on the chosen altitude. The main reason is the interference of the ν_3 SO₂ band with the ν_2 water vapour absorption band. For a given IASI observation,



HRIs calculated for different Jacobians K_h will therefore vary and reach a maximum when the altitude h matches the actual altitude of the SO_2 plume. Therefore, an estimate of the SO_2 altitude can be obtained as

$$\hat{h} = \arg \max_h \text{HRI}(\mathbf{y}, h), \quad (2)$$

90 with the functions $\text{HRI}(\mathbf{y}, h)$ defined as in Eq. 1 with $\mathbf{K} = \mathbf{K}_h$. This is the method explained in detail in Clarisse et al. (2014). We refer to Hyman and Pavolonis (2020) for a probabilistic extension of the method. By means of a theoretical simulation for a tropical atmosphere, it was shown in Clarisse et al. (2014) that the method achieves an accuracy to within 1500 m for SO_2 plumes between 5 and 30 km altitude. This was also shown to be the case in a detailed case study of the 2011 Nabro eruption using CALIOP measurements.

95 The main weakness of the method described above is its dependence on ΔSO_2 . In particular, for large columns, the SO_2 spectral signature saturates and is no longer a good match for the K_h calculated with small variations of SO_2 . Here, this problem is addressed by considering Jacobians both for different altitudes h and for different SO_2 abundances:

$$\mathbf{K}_{\text{SO}_2, h} = \frac{\mathbf{y}(\text{SO}_2, h) - \mathbf{y}_0}{\text{SO}_2} \quad (3)$$

with $\mathbf{y}_0$ a spectrum calculated in the same way as $\mathbf{y}(\text{SO}_2, h)$, but without SO_2 . The altitude estimate $\hat{h}$ becomes:

$$100 \quad (\hat{h}, \widehat{\text{SO}_2}) = \arg \max_{h, \text{SO}_2} \text{HRI}(\mathbf{y}, h, \text{SO}_2), \quad (4)$$

Note that with this change we also obtain a rough estimate of the column abundance $\widehat{\text{SO}_2}$. This is not used for the actual column retrieval detailed in Sect. 3, but serves as a sanity check, as we illustrate below. The Jacobians were calculated for altitudes between 1 and 30 km (in 1-km steps), 32–40 km (in 2-km steps), and 45–60 km (in 5-km steps), and for SO_2 total columns from 1 to 1024 DU in powers of two.

105 For the calculation of the Jacobians, a reference atmosphere is required. To account for spatio-temporal variations, a climatology of humidity, pressure, and temperature profiles was built from ERA5 data (Hersbach et al., 2020) on a monthly basis and on a 20° longitude $\times$ 10° latitude grid. Likewise, a climatology of surface temperatures was obtained on the same grid from IASI L2 data (EUMETSAT, 2022). For each of these 18×18 grid cells, 39 layer heights, and 11 SO_2 columns, Jacobians were calculated using the Atmosphit radiative transfer model (Coheur et al., 2005) and Eq. 3. The spectral range was set to
 110 $1320\text{--}1410 \text{ cm}^{-1}$. To allow for a smooth transition between the different grid cells, new Jacobians are constructed, for each specific IASI observation, via bilinear spatial interpolation of the Jacobians associated with the centres of the four nearest grid cells.

We now detail how the pair $(\bar{\mathbf{y}}, \mathbf{S})$ was determined. As in Franco et al. (2018), we calculate these in an iterative way. Starting from an area-weighted random selection of IASI spectra (such that each equal surface area element of the Earth is equally
 115 represented), a first pair is calculated. This pair is used to calculate SO_2 HRIs. Subsequently, we remove from the initial selection of spectra all those with an HRI above 3, and recalculate $(\bar{\mathbf{y}}, \mathbf{S})$. This procedure is repeated five times. Calculated in this way, the pair $(\bar{\mathbf{y}}, \mathbf{S})$ is built from spectra containing very little to no spectral signature related to SO_2 . The inverse $\mathbf{S}^{-1}$ is calculated as a pseudo-inverse as in Clarisse et al. (2023), making the HRI more robust against the (minor) instrumental



changes that occurred over time for each IASI instrument. Despite this, it was found that the resulting SO₂ HRI time series still exhibited small discontinuities coinciding with instrumental changes. In addition, small offsets between the different IASI instruments were found in the average HRIs. For this reason, it was decided to calculate and use different $(\bar{y}, \mathbf{S})$ for each month of the time series and for each IASI instrument. As we show in Sect. 4.1, the resulting SO₂ time series are fully consistent between the three instruments.

The altitude retrieval is applied to observations with a maximum HRI above 3.25. This and other thresholds defined below were determined empirically based on a few days of observations to maximize sensitivity while limiting spurious detections. The 3.25 threshold allows the detection of very weak enhancements of SO₂ and of SO₂ at plume edges, but comes at the cost of a significant number of false detections. The majority of these are caused by random noise in the spectra and are distributed at random locations globally. To remove these false detections, we set a stricter threshold of 5 for isolated observations (i.e., those observations with no other detections within a distance of 0.75°), a threshold of 4.6 for isolated pairs of observations, and a threshold of 4 for isolated groups of three observations. Due to surface emissivity features, frequent false detections occur at low altitude over the Sahara Desert and desert areas of the Middle East and the United States. For this reason, when the retrieved altitude is below 3 km, we apply an HRI threshold of 7.15 over these areas. The same HRI thresholds are used to select the observations for which columns are retrieved (see Sect. 3).

To reduce noise at the edge of large plumes, each retrieved altitude is replaced by the median of all retrieved altitudes within a distance of 0.75°, including the altitude from the pixel under consideration. This is applied to observations with an HRI below 36. There are two cases where the retrieved altitude is not used but replaced by the median of neighbouring observations instead. The first is when $\widehat{\text{SO}}_2$ is large (above 64 DU), but the corresponding HRI is low (below 29). The second is when the retrieved altitude exceeds 23 km with an HRI below 36. Such retrievals are almost always erroneous, and since the vast majority of detected SO₂ is at altitudes below this, these altitudes are also replaced by the median of neighbouring altitudes.

2.2 Brightness temperature difference method

For very large SO₂ columns, there is a simple alternative method for constraining the altitude. In such cases, the channels most sensitive to SO₂ saturate and their brightness temperature (BT) T_{SO_2} tends towards the local air temperature of the SO₂ plume. This is valid when absorption by water vapour above the plume can be neglected, which is the case for plumes above 7 km. The lowest altitude whose temperature matches T_{SO_2} immediately provides a lower bound on the altitude. Here, we used the 1371.50 cm⁻¹ channel, which is also used for the SO₂ retrieval (see Sect. 3.1). The altitude retrieved by this method is used in the final product when it is higher than the altitude retrieved by the main HRI-based altitude retrieval algorithm.

2.3 Examples and comparison with CALIOP

In this section, we present several examples of the SO₂ detection and layer height retrievals. For each example, shown in Figs. 1–6, we present the maximum HRI (panel a), the retrieved SO₂ heights ($\hat{h}$) (panel b), the retrieved SO₂ vertical column density (VCD) estimates $\widehat{\text{SO}}_2$ (panel c), and an SO₂ detection map (panel d) also showing which altitude retrieval method was used (HRI or BT-based). For each case, we compared the IASI-retrieved SO₂ altitudes with coincident measurements from

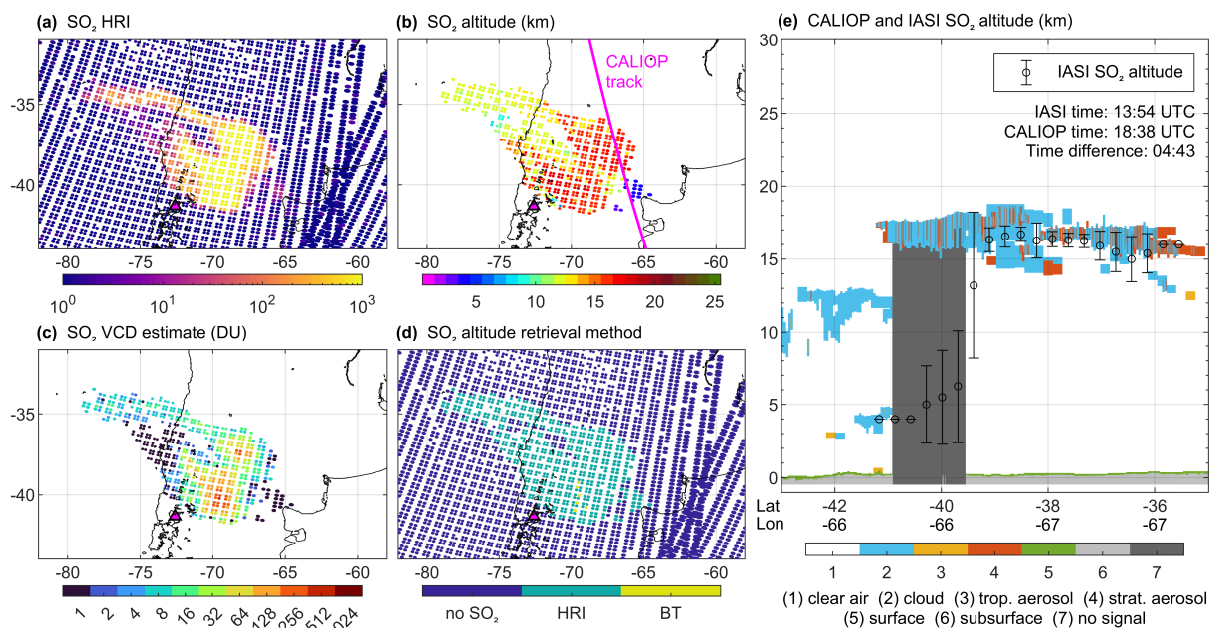


Figure 1. (a) SO₂ HRI calculated from IASI/Metop-A observations on 23 April 2015 (morning overpasses) during the Calbuco eruption (magenta triangle). (b) Retrieved SO₂ plume altitude (in km) and (c) corresponding estimate of the SO₂ vertical column density (VCD; in DU). (d) SO₂ detection and method used to retrieve the SO₂ altitude. (e) Comparison between the CALIOP VFM product along the track shown in b and the collocated IASI SO₂ altitudes. Error bars indicate the $\pm 1\sigma$ standard deviation. *Time difference* denotes the average time difference between CALIOP and the collocated IASI measurements.

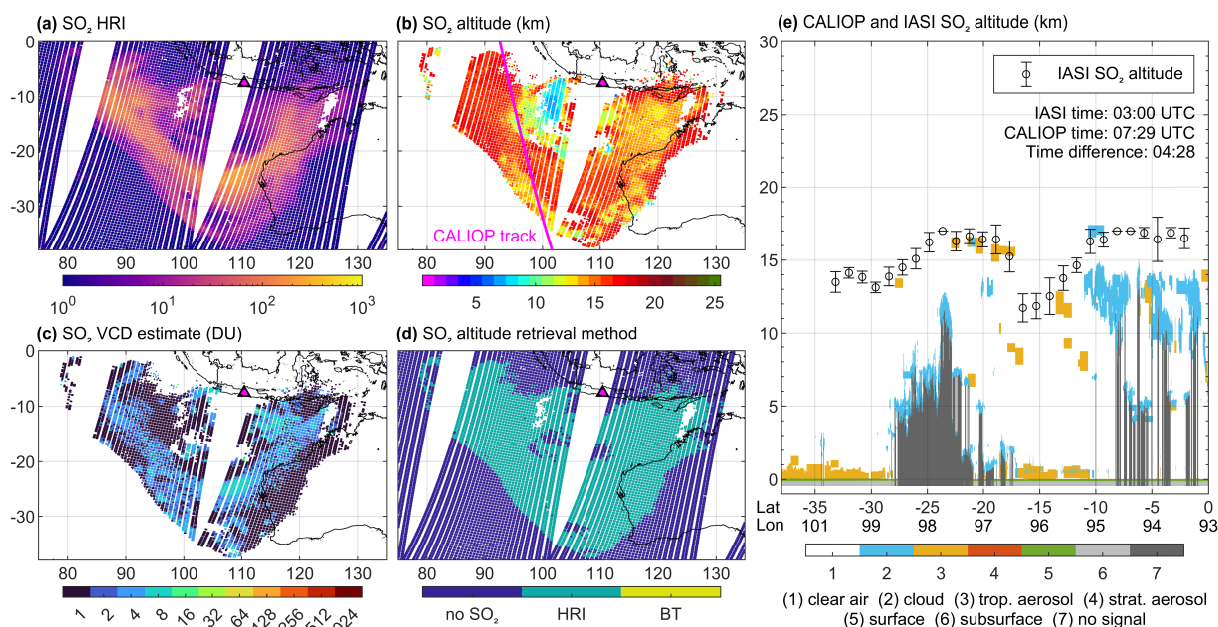


Figure 2. Same as Fig. 1, but for IASI/Metop-A observations on 8 November 2010 (morning overpasses) during the Merapi eruption.

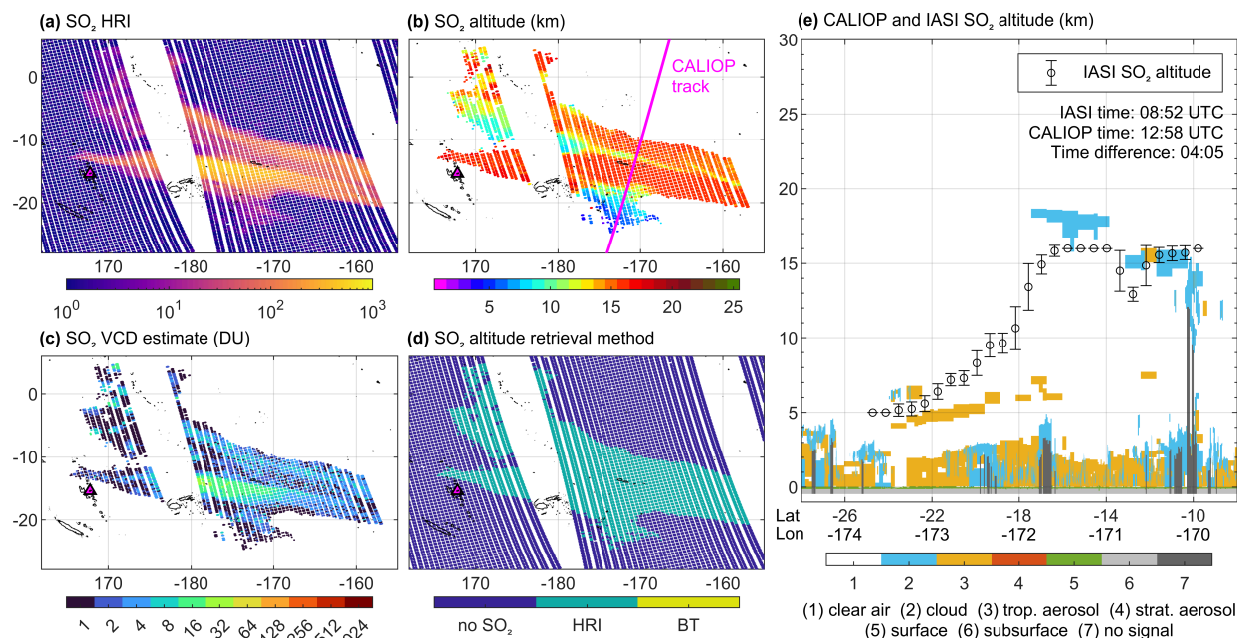


Figure 3. Same as Fig. 1, but for IASI/Metop-B observations on 29 July 2018 (evening overpasses) during the Ambae eruption.

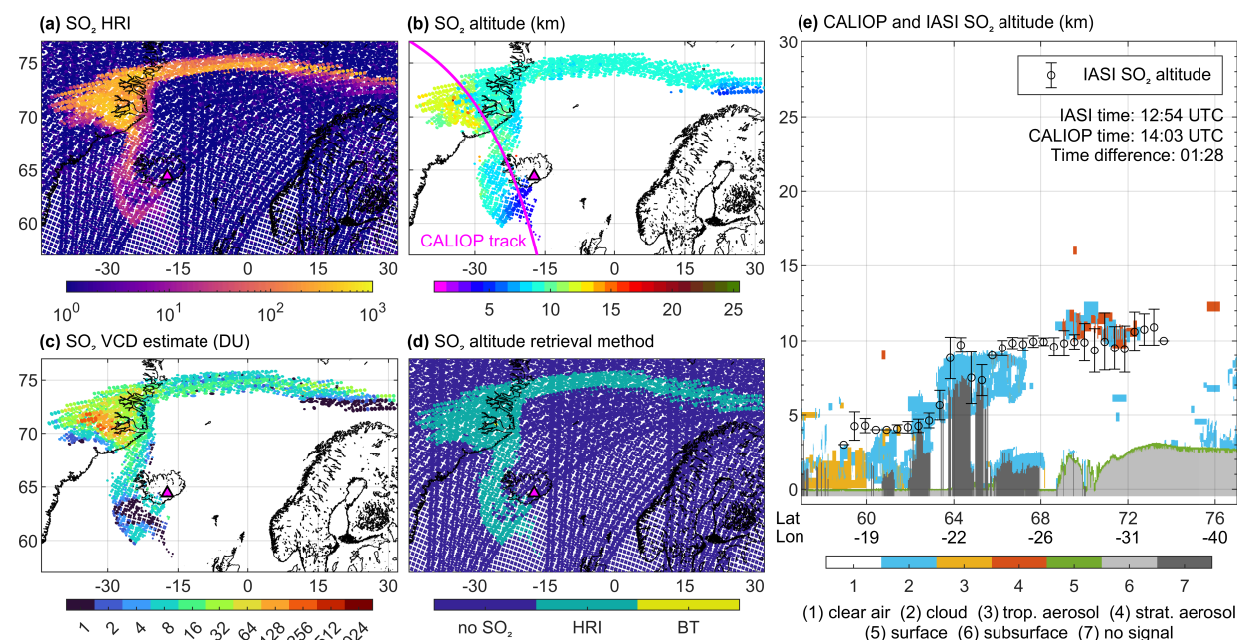


Figure 4. Same as Fig. 1, but for IASI/Metop-A observations on 23 May 2011 (morning overpasses) during the Grímsvötn eruption.



the Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument onboard the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) platform (Winker et al., 2009, 2013). Specifically, we used version 4.51 of the Lidar L2 5-km Vertical Feature Mask (VFM) product, which provides the vertical and horizontal distribution of cloud and aerosol layers (Kim et al., 2018), and is available from June 2006 until June 2023. While not sensitive to SO₂, the CALIOP measurements are sensitive to sulphate aerosols, which are a good proxy for the presence of SO₂. CALIOP is also sensitive to volcanic ash, which often (but not always) indicates the presence of volcanic SO₂ (Prata et al., 2017). For all examples, we selected one CALIOP overpass intersecting an IASI SO₂ plume (shown in magenta in panel b). The VFM product is shown in panel e of Figs. 1–6 together with collocated average IASI SO₂ altitudes (open circles with error bars). The latter were calculated as follows. First, due to the different overpass times of IASI and CALIOP (~09:30/21:30 and ~01:30/13:30 local solar time at the equator, respectively), we discarded all IASI observations acquired more than 7 hours from the nearest CALIOP measurements. Then, at regular intervals along the CALIOP track, we computed an average IASI SO₂ altitude and its associated $\pm 1\sigma$ standard deviation from the IASI measurements located within 0.5° of the interval centre.

2.3.1 Calbuco, 23 April 2015

The April 2015 Calbuco eruption featured two main eruption pulses, one on 22 April at 21:04 UTC that lasted 1.5 hours, and a second on 23 April at 03:54 UTC that lasted 6 hours (Eaton et al., 2016; Romero et al., 2016). The IASI observations shown in Fig. 1 are from the morning overpass on 23 April, approximately 17 hours after the eruption started. Consistent with the evolution of the eruption, two main plumes are seen by IASI both reaching 16–17 km high. The $\widehat{\text{SO}}_2$ distribution shows good consistency with the HRI distribution, with the largest values seen in the centre of the plumes, which demonstrates a clear dependence of the Jacobians on the total column abundance. Panel d shows that the BT-based altitude retrieval method is only used for a few observations in the second plume. The CALIOP observations at 15–18 km largely confirm the retrieved IASI altitudes. Both CALIOP and IASI also see a smaller plume at 41° S, 66° W at an altitude of 4 km. Note that this particular example motivated the inclusion of variable SO₂ abundances for the Jacobians in the HRI-based altitude retrieval method. The previous version of the algorithm, which used a fixed column of 5 DU for the Jacobians, was retrieving plume heights as low as 9 km in the most saturated part of the plume.

2.3.2 Merapi, 8 November 2010

In late October and early November 2010, Merapi produced a series of explosive eruptions, with the largest SO₂ emissions occurring on 3–5 November (Surono et al., 2012). The selected IASI overpass on 8 November (Fig. 2) already shows a somewhat diluted plume mainly present between 13 and 17 km. This is consistent with CALIOP zonal averages between 5 and 11 November, which show that the bulk of the volcanic sulphate aerosols were located between 14 and 17 km (Shibata and Kinoshita, 2016). The CALIOP track shown here indicates a good agreement for latitudes below 17° S. Between 17° S and 10° S, aerosols are seen between 8 and 12 km, whereas collocated IASI SO₂ altitudes are above 11 km. This discrepancy is likely the result of the ~4.5-hour time difference between the IASI and CALIOP measurements. Indeed, directly west-southwest of the volcano, we derive with IASI SO₂ altitudes between 6 and 12 km for a plume that had drifted further

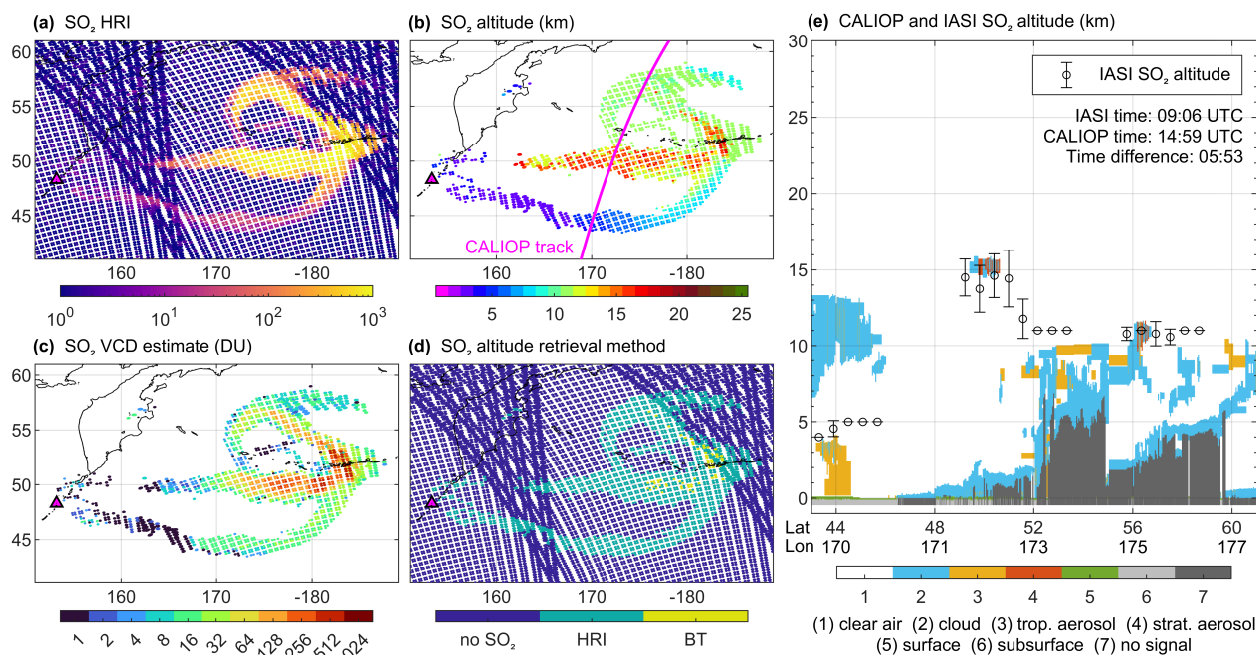


Figure 5. Same as Fig. 1, but for IASI/Metop-B observations on 23 June 2019 (evening overpasses) during the Raikoke eruption.

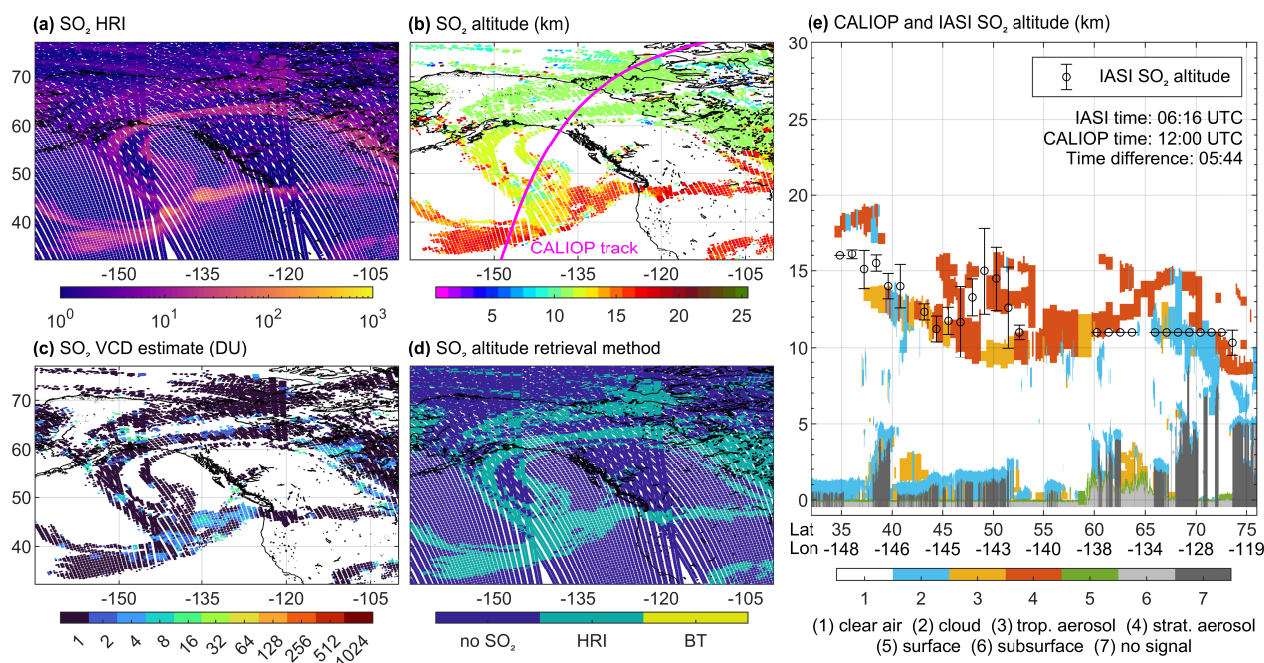


Figure 6. Same as Fig. 1, but for IASI/Metop-B observations on 22 July 2019 (evening overpasses) in the wake of the Raikoke eruption.



185 westwards in the hours separating the overpass of the two sounders (panel b). For the same reason, the part of the plume north
 of 8° S was likely no longer present at the time of the CALIOP overpass.

2.3.3 Ambae, 29 July 2018

The 2017–2018 eruptions of Ambae volcano in Vanuatu featured several major degassing periods, with the most intense one
 occurring in July 2018 and the largest SO₂ emissions on 28 July 2018 (Bani et al., 2025). Figure 3 shows an IASI/Metop-B
 190 overpass on the day after. The CALIOP track shows three altitude ranges: the northernmost part is between 15 and 16 km in
 good agreement with IASI. The next part between 17° S and 14° S is located between 17 and 19 km; our retrievals slightly
 underestimate it, placing it at 16 km. Finally, below 17° S, there is a large tropospheric plume extending from 4 to 7 km high.
 IASI altitudes range from 5 to 10 km below 18° S. Between 16° S and 17° S, the low- and high-altitude plume layers are seen to
 overlap in the CALIOP data. For this part, IASI SO₂ altitudes are derived between 10 and 15 km, positioned midway between
 195 the two layers.

2.3.4 Grímsvötn, 23 May 2011

The next example is that of the Grímsvötn eruption that started on 21 May 2011. The well-documented eruption plume featured
 a high-altitude SO₂-rich part that drifted north and northwest and a low-altitude ash-rich part that was transported south and
 southeast (Moxnes et al., 2014; Prata et al., 2017). A fortunate CALIOP overpass on 23 May intersected both parts, as shown in
 200 Fig. 4. The same overpass was analysed in Carboni et al. (2016) and Prata et al. (2017). The lowest part of the plume is seen by
 IASI at 4 km, whereas CALIOP indicates ash altitudes between 1 and 5 km. Given that this plume was mostly ash, with only
 trace amounts of SO₂, this represents a satisfactory level of agreement. Further along the CALIOP track, IASI altitudes range
 between 7 and 10 km, consistent with the layer top heights seen by CALIOP, even though these are classified as clouds. Over
 Greenland, IASI retrieves altitudes between 8 and 12 km, slightly below the CALIOP features seen between 10 and 12 km.

205 2.3.5 Raikoke, 23 June and 22 July 2019

The 21–22 June 2019 Raikoke eruption consisted of a series of large explosive events that took place in a period of about
 12 hours (starting at 17:50 UTC), followed in the subsequent days by minor low-altitude emissions (Horváth et al., 2021;
 Bruckert et al., 2022; Vernier et al., 2024). The eruptions were rich in both ash and SO₂. The chosen IASI overpass on 23 June
 2019, approximately 39 hours after the start of the eruption, shows an extensive plume reaching 15 km high (Fig. 5). The IASI
 210 altitude retrievals are largely confirmed by CALIOP: the northern part of the plume reaches 11 km for IASI and 8–11 km for
 CALIOP, while the central part reaches 13–16 km for IASI and 15 km for CALIOP. The freshest part of the plume, originating
 from post-eruptive degassing, is slightly overestimated by IASI at 4–5 km compared to 0–4 km for CALIOP. The almost
 6-hour overpass time difference could be in part responsible for the height difference, given that the plume is moving eastward
 and that the retrieved altitudes are lower closer to the volcano.

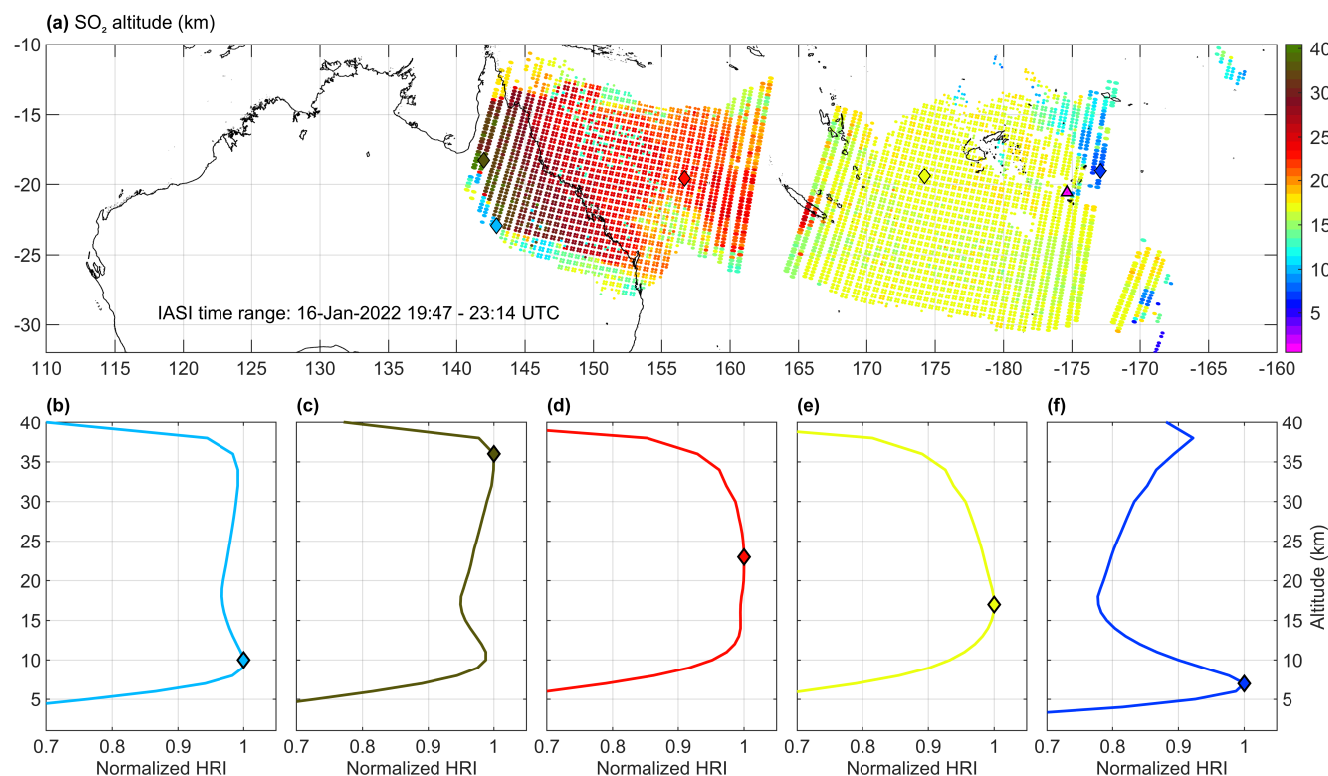


Figure 7. (a) Retrieved SO₂ altitude from IASI/Metop-B observations on 16 January 2022 during the Hunga Tonga (triangle) eruption. (b–e) Normalized HRI profiles for four IASI observations indicated by the diamond markers in a. In each profile, the diamond marks the altitude of the maximum HRI value, corresponding to the SO₂ altitude.

215 Figure 6 shows the IASI SO₂ altitude retrievals one month after the eruption (22 July). As confirmed by the column retrievals presented in the next section, most of the identified SO₂ is below 1 DU, except for those observations with elevated HRI (> 100) observed around 45° N, 140° W. Overall, and as expected, the SO₂ altitude distribution of these aged plumes is noisier than that of the fresh plumes shown earlier. At high latitudes (> 60° N), the retrieved altitudes are around 11 km, whereas at lower latitudes the retrieved heights reach around 17–18 km. The CALIOP data show multiple thick aerosol layers at altitudes
 220 between 9 and 19 km. Overall, the agreement is reasonably good, especially given the low SO₂ levels and the multi-layered nature of the plumes. However, it should be noted that the highest altitudes seen by CALIOP are rarely reproduced by IASI. This is seen here for the plume at 18–19 km, but also for other CALIOP–IASI comparisons of the aged Raikoke plumes. It is also the case for the long-lived volcanic air masses trapped in persistent anticyclones, which are documented in detail in Khaykin et al. (2022) and Fromm et al. (2025). Between 4 and 8 August, when IASI still easily detects the SO₂ within the
 225 anticyclone moving below 40° N, we retrieve altitudes typically below 20 km compared to 22–23 km seen by CALIOP.

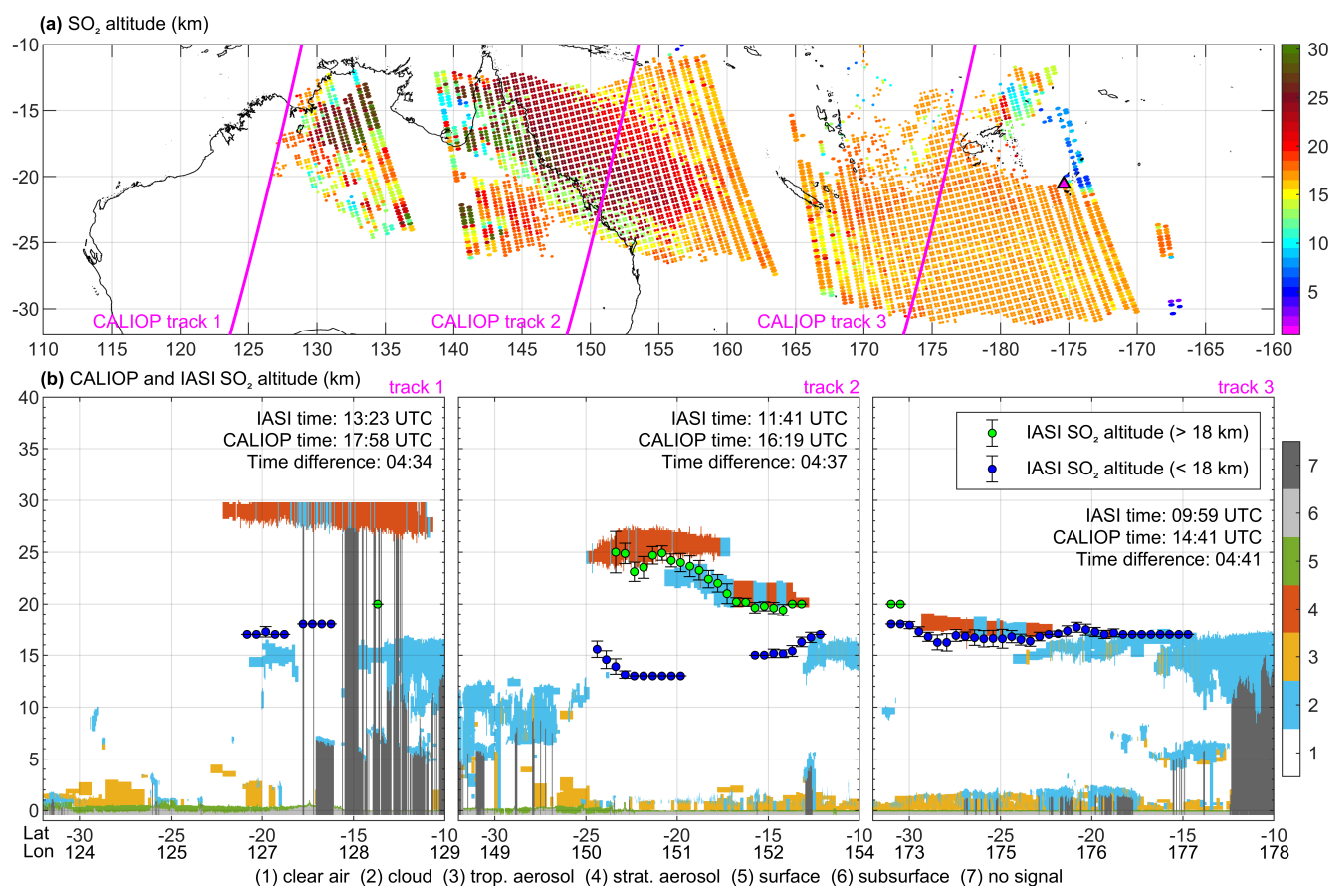


Figure 8. (a) Retrieved SO₂ plume altitude from IASI/Metop-B observations on 17 January 2022 during the Hunga Tonga (triangle) eruption. (b) Comparison between the CALIOP VFM product along three successive tracks shown in a and the collocated IASI measurements, with retrieved SO₂ altitudes below and above 18 km shown as blue and green dots, respectively. Error bars indicate the $\pm 1\sigma$ standard deviation. *Time difference* denotes the average time difference between CALIOP and the collocated IASI measurements.



2.3.6 Hunga Tonga, 17 January 2022

After smaller eruptions in December 2021, Hunga Tonga erupted on 13 January 2022, forming a large umbrella cloud near the tropopause at 16–18 km. This event served as a precursor to the Plinian eruption that began at approximately 04:00 UTC on 15 January. Two umbrella clouds developed: a lower one at 15–19 km and an upper one at about 28–34 km, with a small overshoot reaching 55–58 km (Carn et al., 2022; Carr et al., 2022; Gupta et al., 2022).

Figure 7a shows the SO₂ altitudes retrieved from IASI measurements on 16 January from 19:47 to 23:14 UTC. Retrieved altitudes are mostly in the range 10–36 km, with the highest altitudes seen furthest west and downwind, consistent with transport by stronger mid-stratospheric winds relative to those lower down (Baron et al., 2023; Li et al., 2023). In the southern part of the plume west of 155° E, altitudes below 17 km are also seen, but these are implausible given the aforementioned transport. In fact, in this part of the plume, SO₂ altitudes are seen to be located either above or below 18 km, with few observations in the range 17–19 km. Upon investigation, this appears to result from the presence of two local competing maxima in the HRI(*h*), above and below the tropopause. This is illustrated in panels b–e of Fig. 7, which show the normalized HRI profiles for selected locations in the plume. Panels b and c show examples of the dual maximum. Note also that by design, altitudes above 23 km are never selected for HRIs below 36 (see Sect. 2.1), explaining the lower retrieved altitudes at the plume edges. This condition negatively affects the altitude retrieval for the Hunga Tonga plume, but was imposed to improve the overall performance of the algorithm for the rest of the IASI time series.

The CALIOP overpasses for 16 January are unfortunately not well collocated with respect to the IASI observations. For this reason, we show in Fig. 8 the comparison with CALIOP for 17 January, from 09:59 to 13:23 UTC. Consistent with what is observed for IASI, the CALIOP measurements reveal aerosol layers between 17 and 30 km (the upper limit of the VFM product), with the altitudes increasing from east to west. For the easternmost part of the plume, the retrieved IASI SO₂ altitudes between 16 and 18 km are in good agreement with CALIOP (track 3 in Fig. 8). The part west of 160° E again displays competing altitude estimates below and above 18 km. To facilitate comparison with CALIOP, these two groups of observations are averaged separately in Fig. 8b. As the CALIOP–IASI comparison of the middle section (track 2) shows, when the higher altitude is selected, the match is very good, with altitudes of 20–27 km for CALIOP compared to 19–25 km for IASI. At first sight, the westernmost CALIOP transect (track 1), with altitudes above 28 km, appears to have almost entirely missed the volcanic plume detected by IASI. However, considering the ~4.5-hour time difference between the observations and the westward transport, CALIOP intersected the westernmost part of the plume where IASI retrieves maximum altitudes in the range of 28–32 km, again in good agreement with CALIOP. Even though the generic IASI altitude retrieval clearly has its limitations for stratospheric plumes, 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 SO₂ 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.



3 Column retrieval

There are several methods available for retrieving SO₂ column abundances from measurements by high-resolution IR sounders. These include approaches relying on fitting the observed spectra with a forward model (Clarisse et al., 2008; Clerbaux et al., 2008; Carboni et al., 2012; Zeng et al., 2025), look-up-tables of simulated spectra (Prata and Bernardo, 2007), HRI-type indices (Walker et al., 2012; Bauduin et al., 2016; Taylor et al., 2018; Hyman and Pavolonis, 2020) and look-up-tables of differences of brightness temperature (DBTs) between selected channels (Clarisse et al., 2012). Our retrieval scheme combines a DBT-based method for high SO₂ loadings with an HRI-based method for low loadings. Columns are retrieved assuming all SO₂ is located in a narrow layer at a certain altitude. For each IASI observation, this is done for the altitude obtained by the SO₂ altitude retrieval algorithm, and for all other altitudes between 1 and 60 km.

3.1 Brightness temperature difference method

For large SO₂ columns, and when the plume altitude is above 7 km, the retrieval algorithm is based on brightness temperatures of selected IASI channels. The algorithm is detailed below, but we refer to Clarisse et al. (2012) for additional justifications and illustrations. In what follows, we write spectral radiances $L(\nu)$ in terms of brightness temperatures T using Planck's law
 $L(\nu) = B_\nu(T)$, with ν the wavenumber. Given a homogeneous SO₂ layer at temperature T_{SO_2} , the upwelling radiance $L_{\text{out}}(\nu)$ above the layer satisfies

$$L_{\text{out}}(\nu) = B_\nu(T_{\text{out}}) = B_\nu(T_{\text{in}})t + B_\nu(T_{\text{SO}_2})(1 - t) \quad (5)$$

with $L_{\text{in}}(\nu) = B_\nu(T_{\text{in}})$ the upwelling radiance below the layer and t the layer transmittance. For now, we neglect atmospheric absorption due to other atmospheric constituents in and above the SO₂ plume. Considering Eq. 5 and the Beer–Bouguer–Lambert law $t = e^{-c\text{SO}_2/\cos(\theta)}$, where SO₂ is the column abundance, c is an absorption cross section, and $\cos(\theta)$ is a correction factor that accounts for the satellite zenith angle θ of the observation, one obtains

$$\text{SO}_2 = -\frac{\cos \theta}{c} \ln \left(\frac{B_\nu(T_{\text{out}}) - B_\nu(T_{\text{SO}_2})}{B_\nu(T_{\text{in}}) - B_\nu(T_{\text{SO}_2})} \right). \quad (6)$$

The different quantities in Eq. 6 are determined as follows. The temperature T_{SO_2} is calculated from the atmospheric temperature profile from ERA5 (Hersbach et al., 2020) and the assumed or estimated SO₂ altitude. Two neighbouring channels ('absorption channels') inside the ν_3 band are used to calculate T_{out} , while two other channels ('background channels') outside the ν_3 band of SO₂ are used to estimate T_{in} . These are carefully chosen so that $T_{\text{in}} \approx T_{\text{out}}$ in the absence of SO₂.

Two separate sets of background and absorption channels are used (see Table 1), which were chosen respectively for the retrieval of moderate and large SO₂ columns, as explained below. Table 1 also lists the standard deviation σ_T of $\Delta\text{BT} = T_{\text{in}} - T_{\text{out}}$ on spectra without observable SO₂ quantities. The first set targets channels most sensitive to high-altitude SO₂. Figure 9a shows the behaviour of the signal-to-noise ratio (SNR) $\Delta\text{BT}/\sigma_T$ as a function of SO₂ column for a 16-km high plume in a tropical atmosphere and an 8-km high plume at mid-latitude. The SNR exceeds one for columns above ~ 0.5 DU and increases approximately linearly up to about 50 DU. For columns above 200 DU, the first set of absorption channels

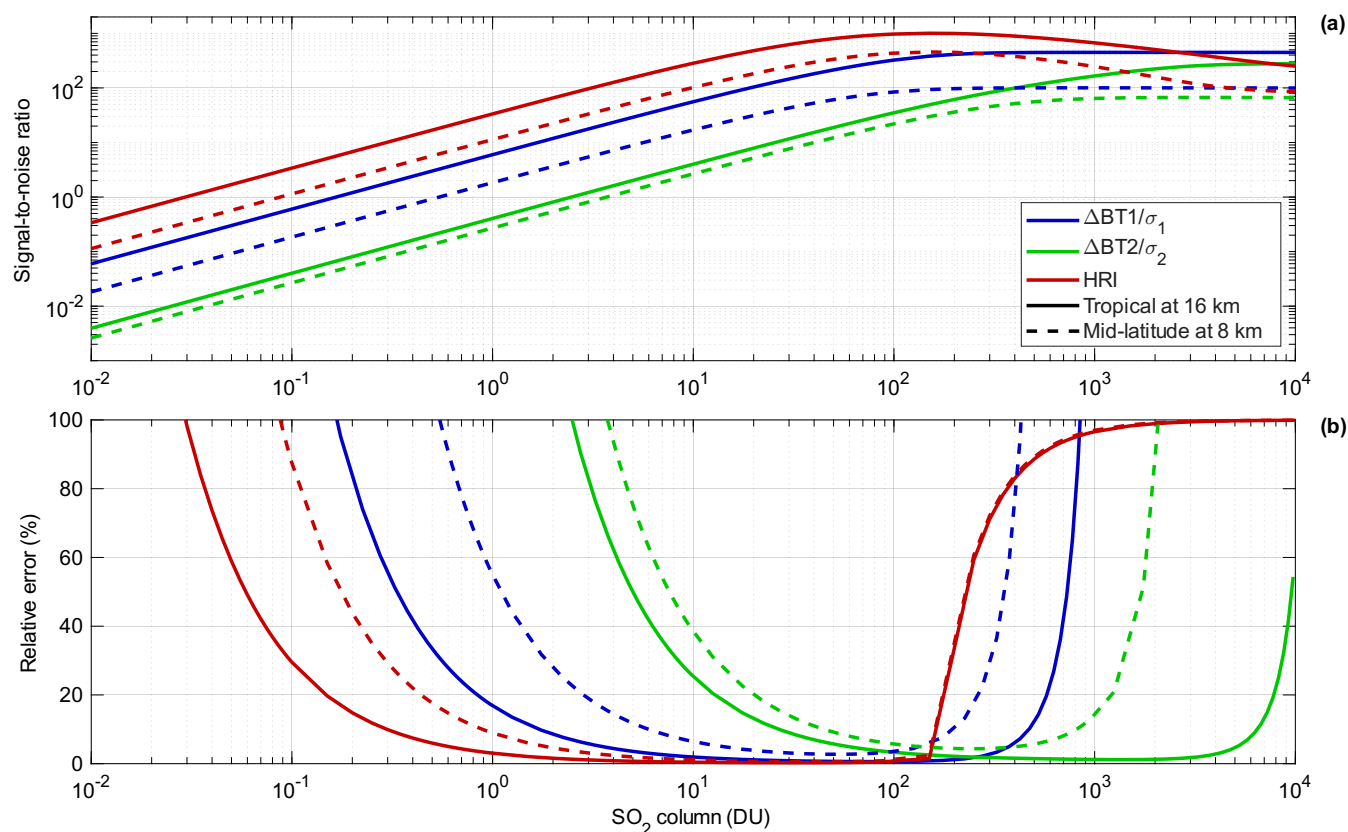


Figure 9. (a) Signal-to-noise ratio as a function of SO_2 column for the different column retrieval approaches (brightness temperature and HRI-based) for a tropical high-altitude SO_2 plume. ΔBT_1 and ΔBT_2 are the brightness temperature differences for the first and second set of channels from Table 1, and σ_1 and σ_2 their respective standard deviations. (b) Corresponding relative retrieval error as function of SO_2 column. These quantities were calculated for a tropical atmosphere with an SO_2 layer located at 16 km with corresponding atmospheric temperature of 195 K and pressure of 113 hPa (solid lines), and a mid-latitude with an SO_2 layer located at 8 km with corresponding atmospheric temperature of 250 K and pressure of 386 hPa (dashed lines).



Table 1. Channels used for the DBT-based column retrieval approach. The standard deviation σ_T was estimated on one day of spectra without observable SO_2 quantities.

Number	Sensitivity	Absorption	Background	σ_T (K)
		channels (cm^{-1})	channels (cm^{-1})	
ΔBT_1	High	1371.50, 1371.75	1407.25, 1408.75	0.15
ΔBT_2	Low	1384.75, 1385.00	1407.50, 1408.00	0.25

290 saturates and can no longer be used to retrieve SO_2 columns accurately. This is illustrated in Fig. 9b, which shows the effect of a perturbation $\Delta\text{BT} + \sigma_T$ on the retrieved column. The second set of channels is less sensitive and only saturates for columns above 1000–5000 DU.

While in the absence of SO_2 $T_{\text{in}} \approx T_{\text{out}}$ for both sets, small biases were observed in the median values of $T_{\text{in}} - T_{\text{out}}$ as a function of time, location, and IASI instrument: (i) The global median values for IASI/Metop-A measurements underwent an abrupt change on 13 April 2015 from -0.05 to -0.1 K, only to return to normal on 7 October 2015. These dates coincide with changes to the IASI-A instrument (see Boynard et al. (2018) and references therein). (ii) While the values of IASI-A and IASI-
 295 C match closely, those of IASI-B exhibit a small offset of 0.05–0.06 K compared to those of the other two instruments. (iii) Finally, the distributions of the median values show slight regional biases of the order of -0.1 to 0 K and -0.2 to 0.3 K for the first and second set of channels, respectively. In each case, fixed offset corrections were applied to the brightness temperatures to counter the observed biases. In particular, regional biases were removed based on a monthly median climatology calculated over the entire 2008–2024 period.

300 The remaining unknown in Eq. 6 is the absorption cross section c . This coefficient not only depends on the pressure and temperature of the SO_2 layer, but also on the SO_2 abundance (see Clarisse et al., 2012). Forward simulations were used to construct look-up-tables of $c(T, P, \text{SO}_2)$ for both sets of channels on a grid of 553 temperature–pressure pairs and 17 SO_2 columns ranging from 1 to 10,000 DU. For this new version of the SO_2 product, the look-up-tables have been re-generated on a finer grid compared to Clarisse et al. (2012), who used 82 temperature–pressure pairs. Pressure and temperature pairs
 305 were selected based on those found in the 13,495 well-sampled atmospheric profiles from the ECMWF ERA-40 reanalysis (Chevallier, 2001). Pressures range from 0.1 to 600 hPa on 41 levels, covering altitudes from 5 to 60 km. The temperature varies in steps of 5 K between a minimum and maximum that depend on the pressure. For each temperature–pressure pair, 10 corresponding ERA-40 profiles were selected for which the temperature and pressure match the specified pair at some altitudes. The absorption cross section c was then calculated as the median over these 10 simulations using Eq. 6, for each of
 310 the 17 different SO_2 column abundances. With these look-up-tables and Eq. 6, SO_2 columns can be retrieved. Pressures and temperatures are obtained from the retrieved SO_2 altitudes and collocated ERA5 profiles. Because of the dependence of c on SO_2 abundance, SO_2 is calculated in an iterative way. Starting from a constant value of c , a first estimate of SO_2 is obtained,

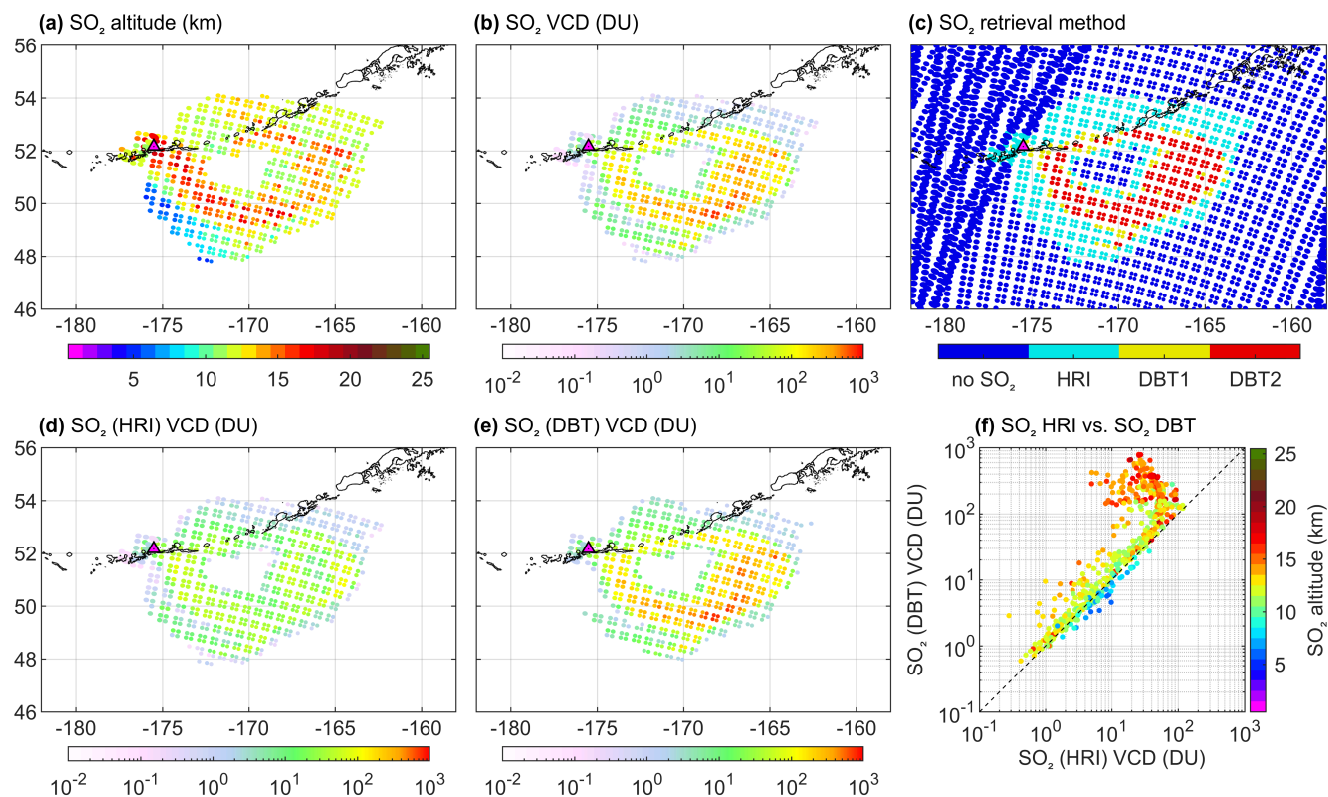


Figure 10. IASI/Metop-A retrievals from 8 August 2008 (morning overpasses) during the Kasatochi eruption. (a) Retrieved SO_2 altitude. (b) SO_2 VCDs. (c) Retrieval approach. (d) HRI-based SO_2 VCDs. (e) DBT-based SO_2 VCDs. (f) Comparison between HRI-based and DBT-based SO_2 VCDs, colour-coded by the retrieved SO_2 altitude. All VCDs and altitudes are in DU and km, respectively.

which then yields a better estimate of $c(T, P, \text{SO}_2)$ and subsequently SO_2 . This procedure is repeated ten times, even though convergence is usually obtained after a few iterations.

315 A final subtlety arises for cases where there is non-negligible absorption by water vapour above the SO_2 layer. Based on the simulations presented above, it was found that on average, and to a good approximation, a partial H_2O column above the SO_2 layer in units of $10^{21} \text{ molec} \cdot \text{cm}^{-2}$ leads to a temperature decrease of

$$\Delta T \approx 0.0033\text{H}_2\text{O}^3 - 0.13\text{H}_2\text{O}^2 + 2.0\text{H}_2\text{O}, \quad (7)$$

in both absorption and baseline channels. This effect is taken into account by subtracting this value from T_{SO_2} before applying
 320 Eq. 6. The correction is mostly below 2 K. The above-plume H_2O column is derived from ERA5 humidity profiles collocated with the retrieved IASI altitudes.

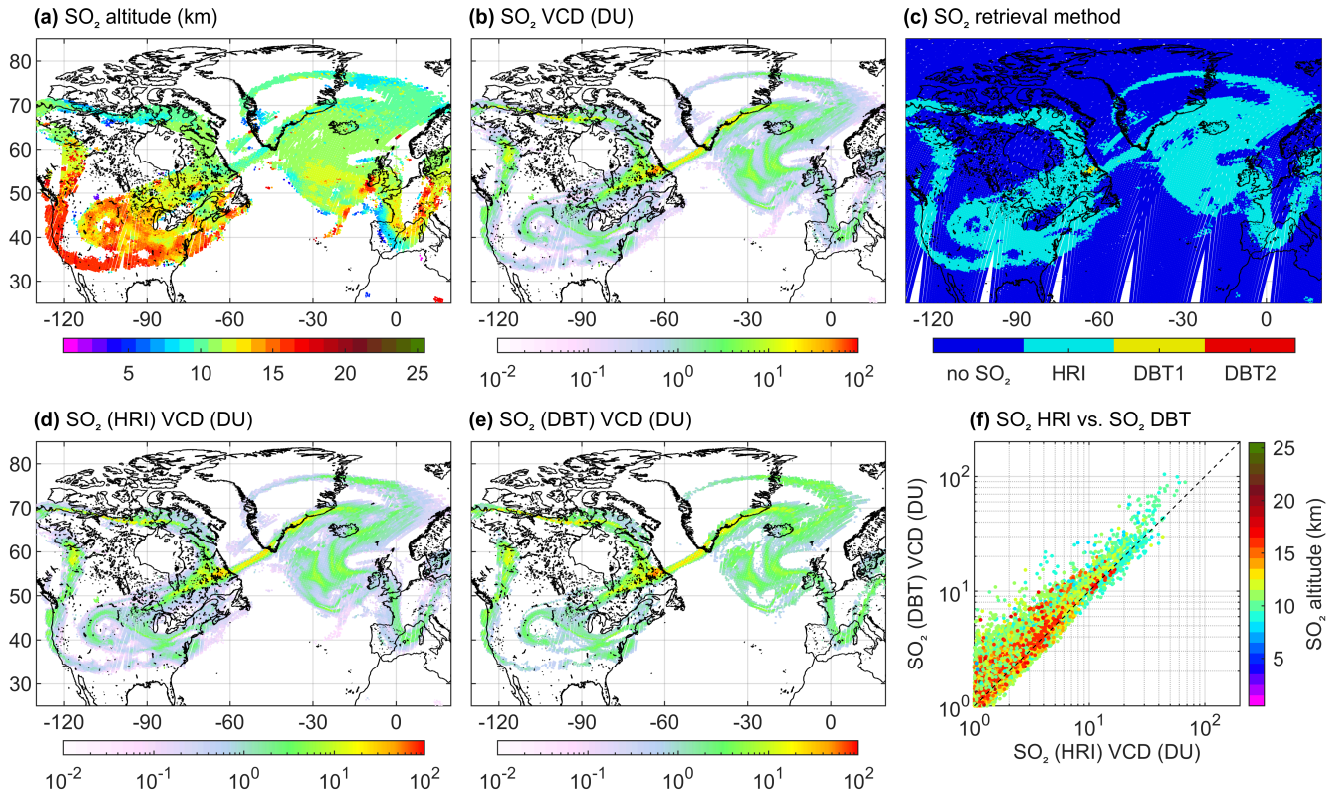


Figure 11. Same as Fig. 10, but for the IASI/Metop-A observations on 15 August 2008, in the wake of the Kasatochi eruption.

3.2 Hyperspectral range index

Just like the brightness temperature difference ΔBT introduced in the previous section, the quantity $HRI(y, h, SO_2)$ is proportional to the SO_2 abundance in the observed spectrum y , as illustrated in Fig. 9a. For this example, an HRI of one (the noise level) is reached for a column as low as 0.03 DU. We also observe that the relationship is linear for columns up to about 10 DU, and that for columns above 100–200 DU the HRI actually decreases with increasing columns. However, below 100 DU, there is a 1-to-1 correspondence between column and HRI, which forms the basis for the HRI-based column retrieval.

Using the same climatology and latitude-longitude grid as presented in Sect. 2.1, a monthly look-up table was built for HRI values as a function of SO_2 abundance, for each altitude h . For a given IASI observation, an SO_2 estimate is obtained for each assumed altitude h by one-dimensional interpolation of $HRI(y, h, 1 \text{ DU})$ from the monotonic part of the look-up table. Note that we extrapolate linearly for HRI values below zero to also obtain a retrieval for negative HRIs that typically represent noise. In this way, a column is obtained for each observation. Allowing negative columns results in theoretically unbiased averages (Clarisse et al., 2019). Indeed, for observations with background levels of SO_2 , HRIs are normally distributed around 0, and because of the linearity, the retrieved columns are distributed around 0 DU. The bottom panel of Fig. 9b shows the relative retrieval error of this approach. This method clearly outperforms the DBT-based methods for low columns, achieving for these



examples a relative error below 20% in the range of 0.15–175 DU. For larger columns, the DBT approach performs better, allowing meaningful results up to 10,000 DU.

3.3 The combined product

The HRI-based column retrieval method is applied to all observations and for all altitudes from 1 to 60 km. For all observations with a valid altitude estimate, an SO₂ value is also retrieved using the DBT method. For the latter, we additionally require that the observed temperature T_{in} is larger than T_{SO_2} and that there is sufficient thermal contrast, with $T_{\text{out}} > T_{\text{SO}_2} + 5$ K. When $\Delta BT_1 < -0.5$ K, an SO₂ column is retrieved using the first set of channels, whereas the second set of channels is used only when $\Delta BT_1 < -5$ K and $\Delta BT_2 < -2$ K. In this way, up to three SO₂ columns are obtained, two based on DBTs and one on the HRI. These are combined into one product as follows. First, for altitudes below 8 km, only the HRI method is used. Above this altitude, and when the DBT method with the first set of channels (DBT1) retrieves an SO₂ column larger than 32 DU, that value is used, except when any of the DBT-retrieved columns exceeds 128 DU. In this case, the estimate from the DBT method with the second set of channels (DBT2) is used. In this way, an SO₂(z) column is retrieved for each observation, and for each assumed plume altitude z from 1 to 60 km. A combined IASI-derived altitude-column dataset is obtained from this and consists of the SO₂ columns at the retrieved altitude, with the columns set to 0 DU when no altitude is retrieved. For morning and evening overpasses separately, gridded versions of the SO₂ columns and retrieved altitudes are also available, which allow the calculation of total mass over a geographical area. This combined altitude-column dataset will be discussed in the rest of this paper.

The altitude-dependent columns SO₂(z) that are available for all IASI observations can be used when the SO₂ altitude is known from independent measurements or model simulations. In addition, they allow constructing total column averaging kernels (AVKs) A_z with

$$A_z = \frac{\text{SO}_2}{\text{SO}_2(z)}, \quad (8)$$

with SO₂ the retrieved column at an arbitrary reference altitude. The AVKs can be used to simulate what would be retrieved if modelled SO₂ partial columns M_z were observed (Clarisse et al., 2023):

$$\text{SO}_2' = \sum_z A_z M_z \quad (9)$$

Alternatively, AVKs can be used to obtain columns that are consistent with a prescribed normalized SO₂ profile $m_z = M_z / \sum_z M_z$:

$$\text{SO}_2'' = \frac{\text{SO}_2}{\sum_z m_z A_z} = \left(\sum_z \frac{m_z}{\text{SO}_2(z)} \right)^{-1}, \quad (10)$$

i.e., as a weighted harmonic mean of SO₂(z). Note that these equations are only exact in the linear regime.

The first examples, presented in Figs. 10 and 11, show the fresh and one-week-old volcanic plumes after the August 2008 Kasatochi eruption (Waythomas et al., 2010). Both figures show: (a) the retrieved SO₂ heights, (b) the retrieved SO₂ columns

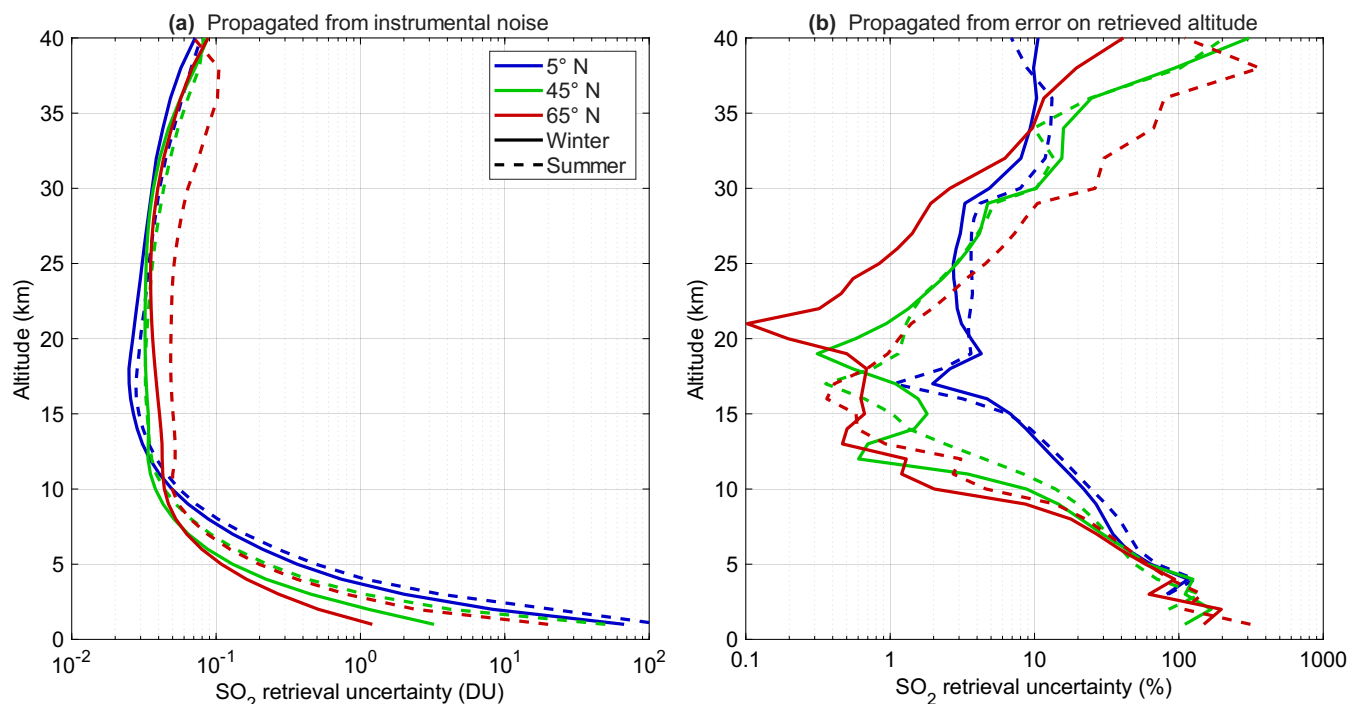


Figure 12. (a) SO₂ retrieval uncertainty due to instrumental noise, as a function of altitude, for three different latitudes and for two different periods of the year. These were calculated as the columns corresponding to an HRI of one. (b) SO₂ retrieval uncertainty due to a 1-km error in the retrieved altitude. The data were calculated from the median of 100–1000 actual observations from six different plumes (winter and summer each at three different latitudes).

(combined product) at the retrieved altitudes, (c) the SO₂ retrieval method used for the combined product, (d) the HRI-based SO₂ columns, (e) the DBT-based SO₂ columns, (f) a scatter plot between the columns shown in (d) and (e). The fresh Kasatochi plume (Fig. 10) features altitudes between 5 and 17 km, with the largest columns seen at the highest altitudes. As expected, the largest SO₂ columns are retrieved with the DBT2 approach, the smallest and lowest columns with the HRI approach, and everything in between with the DBT1 method. Panels d–f illustrate well that the HRI method fails to retrieve columns above 100 DU, while the DBT-based method fails to retrieve the plume edges below 1 DU. For columns between 1 and 100 DU, both methods agree well with each other despite an altitude-dependent bias. The one-week-old plume, shown in Fig. 11, is almost entirely retrieved with the HRI-based approach, even though both retrieval approaches are seen to agree reasonably well. Columns below 10 DU exhibit a larger scatter.

375 3.4 Retrieval errors

There are four main sources of error in the retrieved SO₂ columns, which are discussed below.



3.4.1 Instrumental noise (L1)

Instrumental noise affects the calculated DBTs and HRIs, and these errors propagate to the retrieved columns. Here, we provide estimates of the magnitude of such errors, first considering SO₂ columns above 32 DU. For high-altitude plumes, the DBT-based product is used. Referring to Fig. 9b, we see that relative errors below 5% are attained for columns in the range of 32–300 DU. A relative error below 20% is attained for columns between 1000 and 8000 DU, depending on the atmosphere considered. For altitudes below 8 km, the HRI-based product is used, with relative errors at 5 km typically below 5% for columns up to 150 DU (not shown in Fig. 9b).

Then, we consider SO₂ columns below 32 DU for which the HRI-based product is used exclusively. Figure 12a shows the retrieval error as a function of altitude and latitude. These were calculated from the corresponding SO₂ Jacobians from Sect. 2.1 as the SO₂ columns corresponding to an HRI of one. We see that the highest sensitivity is for plume altitudes above 10 km, reaching a minimum of 0.025 DU for a tropical atmosphere and 0.05 DU at higher latitudes. Below 10 km, the situation reverses, and the tropical atmosphere becomes significantly less sensitive to SO₂ because of interfering H₂O absorption. At 5 km, the uncertainties are in the range of 0.1–0.5 DU, further increasing to 1–100 DU at 1 km. We also see that winter, with its drier atmosphere, provides more favourable conditions for retrieving SO₂.

Taken together, we conclude that for plumes above 8 km, a conservative estimate of the retrieval uncertainty due to the instrumental noise is 0.1 DU + 5% for columns from 0.1 to 300 DU. For low-altitude columns, the retrieval uncertainty varies significantly as a function of the atmosphere and altitude. At 5 km, the uncertainty is below 0.5 DU + 5% for columns in the range of 0.5–150 DU, further increasing at lower altitudes.

3.4.2 Retrieved altitude

Thermal IR retrievals are significantly affected by thermal contrast (TC), which here corresponds to the temperature difference between the SO₂ plume and the brightness temperature of the upwelling radiation from beneath it. Since the altitude of SO₂ is not known exactly, errors in the retrieved altitude propagate into the retrieved column. Figure 12b shows the change in retrieved SO₂ corresponding to a change of 1 km in the assumed plume height. The data were calculated from six different plumes located at approximately 5° N, 45° N, and 65° N latitude, in both winter and summer. For each observation, an error profile was obtained and the median over the entire plume was computed, resulting in the six error profiles shown in Fig. 12b. In the upper troposphere and lower and mid-stratosphere, the retrieval errors are below 5% per km for the tropical plumes and below 1% per km for extratropical atmospheres. Errors increase rapidly at lower altitudes, reaching about 50% at 5 km, and increasing further at lower altitudes. At low altitudes, as the TC is lower, an error in the assumed height translates into a large relative error in the TC and thus in the column. It should be emphasized that errors related to the retrieved altitude can be largely mitigated if accurate third-party information on the altitude or SO₂ profile is available (see discussion related to Eq. 10 in Sect. 3.3).



3.4.3 Other input data

We briefly list here the principal sources of error related to other input data. The DBT algorithm relies on look-up tables of averaged absorption cross sections, which Clarisse et al. (2012) estimated to have an uncertainty of the order of 5%. In addition, the algorithm relies on the temperature of the SO₂ layer from ERA5, which can deviate from the true layer temperature. This type of error has the same effect as an error in the retrieved altitude, and its magnitude will therefore be modest, except for highly saturated plumes where the temperature of the SO₂ layer approaches that of the absorption channels used in the DBT algorithm. The HRI-based algorithm uses a gridded monthly climatology of averaged atmospheres, and local and day-to-day variability of temperature and humidity profiles can induce errors in the retrieved SO₂. The largest errors will be incurred for near-surface SO₂, since temperatures vary the most in the lower troposphere.

3.4.4 Clouds and volcanic ash

As discussed in Clarisse et al. (2012) and Carboni et al. (2019), the presence of clouds and volcanic ash can strongly affect retrieved SO₂. They will mostly cause an attenuation of the SO₂ spectral signature, whether located below or above the SO₂ plume. The HRI algorithm, which is based solely on the magnitude of the spectral signature, will therefore tend to underestimate the retrieved abundances in the presence of clouds or ash. The DBT algorithm accounts explicitly for the magnitude of the upwelling radiance below the SO₂ plume and should therefore be unaffected by underlying clouds. Overlying clouds on the other hand will affect both the absorption and background channels, and depending on the specific conditions will lead to under- or overestimations of the SO₂ abundances (Clarisse et al., 2012).

A statistical analysis was performed to estimate the order of magnitude of this type of error. Considering columns between 1 and 50 DU, daily median columns were calculated separately for cloud-free scenes and scenes with 100% cloud cover, for altitudes between 1 and 20 km. The ratios of these daily values were then averaged for the entire IASI dataset. For the HRI-based algorithm, the SO₂ columns in cloudy scenes were found to be 5–20% lower, depending on the altitude bin, while for the DBT-based algorithm differences were smaller (0–10%). As a complementary test, daily regression slopes were calculated between HRI and DBT-based columns, per altitude bin. The median of these daily values for the entire IASI dataset shows a good consistency between the two approaches for cloud-free scenes, with differences mostly between -5 and 5% depending on the altitude. For cloudy scenes, the HRI-based approach gives on average between 15 and 30% lower columns. These numbers are consistent with the other statistical assessment showing that the HRI-based columns are more affected by clouds.

3.5 Comparisons with TROPOMI

The TROPOspheric Monitoring Instrument (TROPOMI) onboard the Sentinel-5 Precursor (S-5P) platform (Veefkind et al., 2012) provides UV SO₂ measurements in the early afternoon (13:30 local solar time) that complement the morning and evening IASI observations, thereby offering additional temporal coverage for tracking volcanic gas plumes. This is illustrated below using SO₂ column and altitude measurements from consecutive IASI–TROPOMI–IASI overpasses for three fresh volcanic plumes (Figs. 13–15). The TROPOMI SO₂ VCDs and layer heights used here were retrieved from its second UV spectral

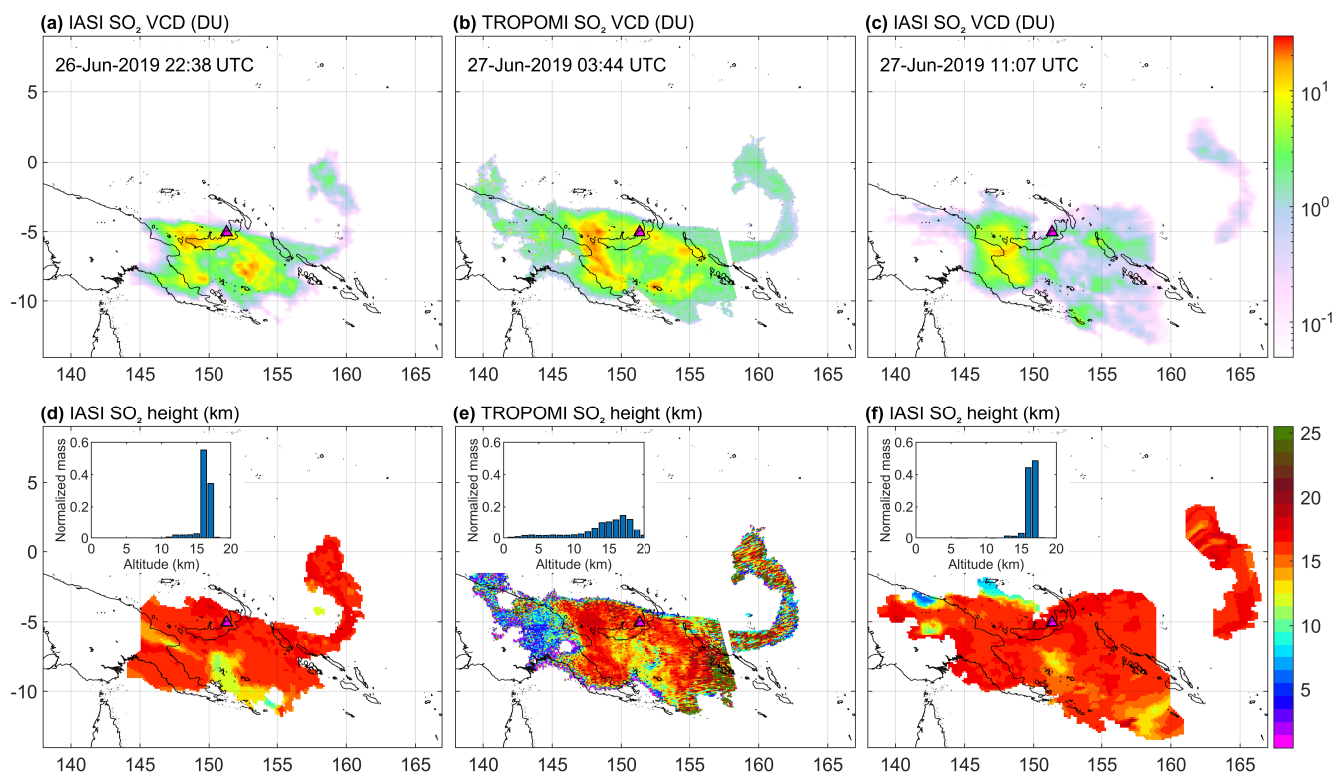


Figure 13. (a–c) SO₂ VCD (in DU) and (d–f) SO₂ altitude (in km) from three consecutive overpasses of IASI and TROPOMI during the eruption of Ulawun in June 2019. Histograms in inset show the corresponding normalized mass profiles.

band (BD2; 305–326 nm) with the Look-Up Table – COvariance-Based Retrieval Algorithm (LUT-COBRA; Theys et al., 2021, 2022), as described in detail by Fabris et al. (2025). Compared with TROPOMI’s third UV band (BD3), BD2 allows the detection of lower SO₂ quantities and the reduction of uncertainties on the retrieved SO₂ columns and layer heights, owing to the stronger SO₂ absorption features and the higher signal-to-noise ratio in BD2. In the following examples, the IASI data are gridded at a $0.125^\circ \times 0.125^\circ$ resolution, whereas the TROPOMI pixels are displayed after excluding negative VCDs and applying a running 3×3 median filter.

The 2019 Ulawun (Papua New Guinea) eruption began on 24 June with detectable precursor gas activity, followed by a Plinian phase characterized by gas-dominated emissions on 26 June, 04:20 UTC (Kloss et al., 2021; McKee et al., 2021b). Later that day (~22:30 UTC), IASI/Metop-A detected a large SO₂ plume from Ulawun, extending both westward and eastward from the volcano, with column values up to 10–20 DU in its central part and a mass largely confined between 16 and 17 km altitude (Fig. 13). Five hours later (27 June, ~03:40 UTC), TROPOMI retrieved a plume consistent with the IASI observations, with comparable column values. While the SO₂ layer heights retrieved by IASI are relatively homogeneous across the plume, those derived from TROPOMI exhibit greater variability, with a larger fraction of the SO₂ mass assigned to lower altitudes. On 27 June, ~11:00 UTC, the second IASI overpass shows the plume transported eastward, with SO₂ confined at the tropical

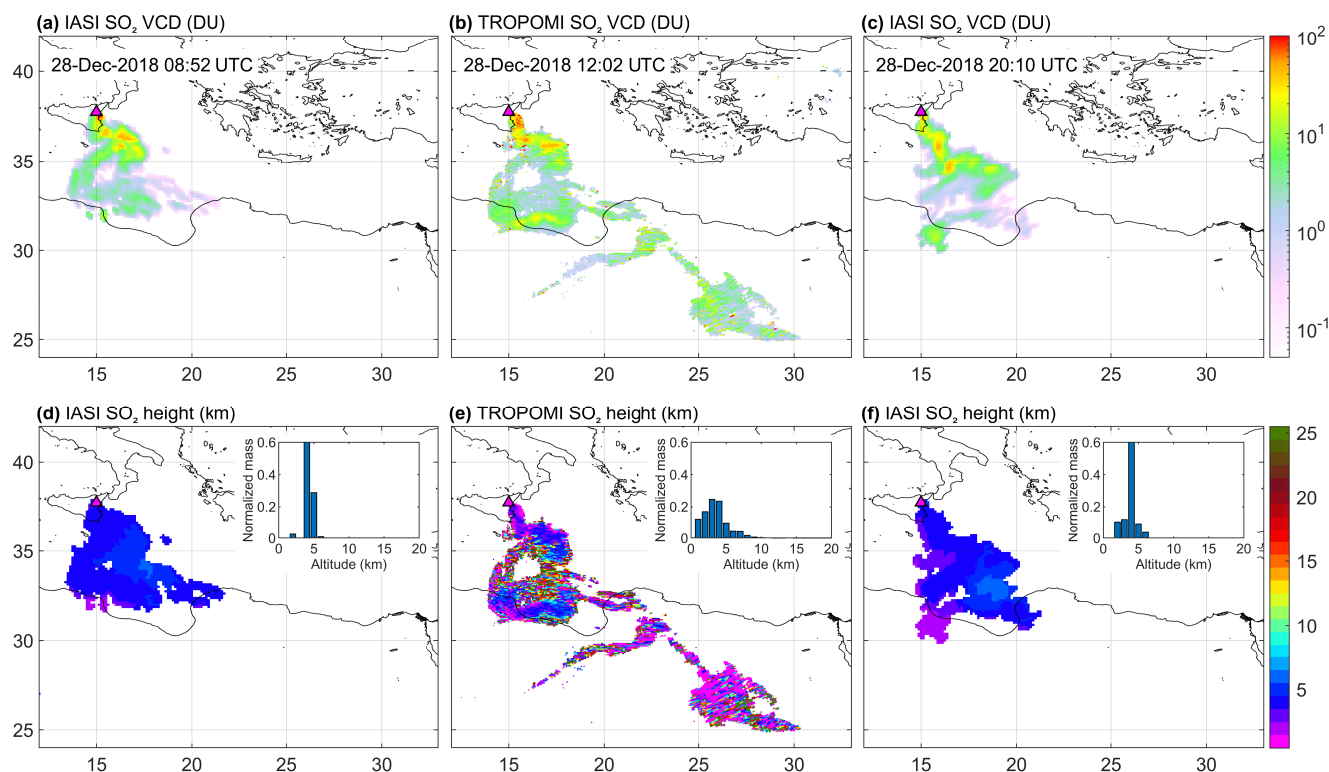


Figure 14. Same as Fig. 13, but during the eruption of Etna in December 2018.

tropopause. A notable difference is the detection by TROPOMI of a low-altitude (< 10 km) portion of the plume over Papua
 455 New Guinea. Although the first IASI/Metop-A overpass does not fully sample this region (Fig. 13), the other IASI sounders
 also do not detect this low-altitude component of the plume. This is attributable to the limited sensitivity of IASI to low-altitude
 tropical SO_2 (see Fig. 12a).

The second example presents an SO_2 plume from Etna during the "Christmas" eruption of December 2018, transported
 southward over the Mediterranean Sea (Fig. 14). Following the major explosive phase on 24 December 2018, Etna continuously
 460 ejected gas and ash until 30 December (Corradini et al., 2020, 2021). On 28 December, the SO_2 columns retrieved from both
 IASI/Metop-B and TROPOMI peak between 50 and 100 DU near the volcano and decrease to values not exceeding 20–
 30 DU toward the North African coastline. The two sounders show good agreement in terms of SO_2 columns and layer
 heights. However, plume portions characterized by low SO_2 columns (below 1–2 DU) exhibit noisier altitude retrievals in the
 TROPOMI data. Moreover, TROPOMI detected a low-altitude SO_2 plume (1–2 km) over North Africa, which corresponds
 465 to the remnant of an earlier plume emitted by Etna 24–48 hours before the analysed overpasses. The absence of this low-
 altitude plume component in the IASI/Metop-B observations is explained by IASI's reduced sensitivity to near-surface layers,
 particularly over land during winter (Di Gioacchino et al., 2024).

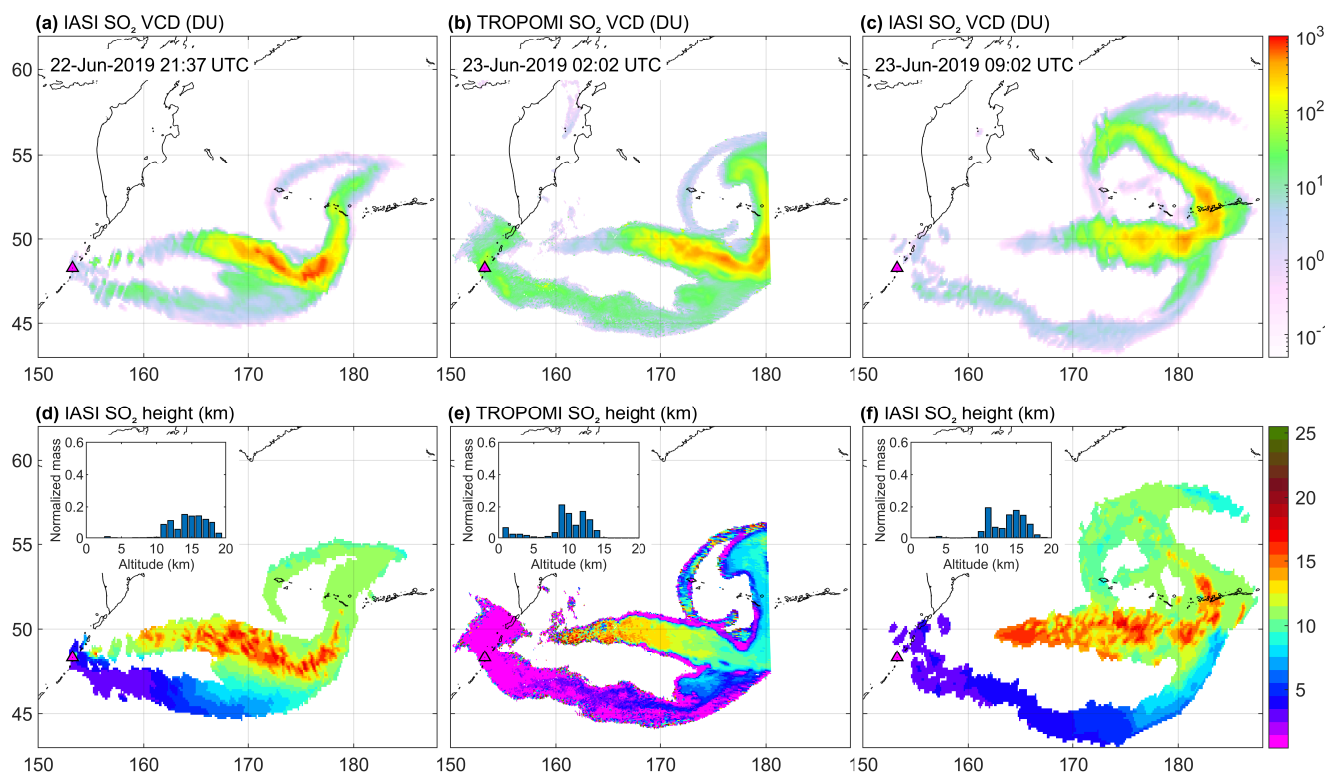


Figure 15. Same as Fig. 13, but during the eruption of Raikoke in June 2019.

The large SO₂ plume produced by the June 2019 Raikoke eruption presented a complex vertical structure, as discussed in Sect. 2.3.5. On 22 and 23 June, IASI/Metop-C retrievals revealed three distinct altitude features (Fig. 15): a northern
 470 branch of the plume located at 10–11 km, a central branch containing the bulk of the SO₂ mass injected above the tropopause (> 13 km and reaching 17–18 km), and a southern, low-altitude feature at 4–5 km corresponding to post-eruptive SO₂ degassing (Horváth et al., 2021; Bruckert et al., 2022; Vernier et al., 2024). Both IASI and TROPOMI retrieved broadly consistent SO₂ columns, exceeding 100 DU in the northern branch and largely surpassing 300–400 DU in the central plume. Peak values even exceeded 900 DU in the IASI overpass on 22 June, in agreement with Hedelt et al. (2019). However, while TROPOMI
 475 detected the same vertical plume structure as IASI, the retrieved layer heights are systematically lower by ~2 km, which complicates a direct comparison between the two sounders. For example, higher columns retrieved by TROPOMI in the degassing plume may result from lower retrieved layer heights relative to IASI. While IASI-derived altitudes showed good agreement with CALIOP observations (Sect. 2.3.5), the lower altitudes retrieved from TROPOMI could result from the particularly high volcanic ash content of the Raikoke plume (McKee et al., 2021a; Bruckert et al., 2022; Vernier et al., 2024).



480 4 Time series

The new IASI SO₂ retrievals presented in this study have allowed us to construct a consistent 18-year global record (July 2007 – December 2025) of SO₂ measurements, using observations from a single type of IR satellite sounder. To this end, we combined measurements from the entire time series of IASI/Metop-A, -B, and -C. Owing to the twice-daily overpasses of each IASI sounder, this SO₂ product enables detailed monitoring of volcanic emissions and the day-to-day evolution of volcanic
 485 plumes.

As an illustration, Fig. 16 presents the twice-daily SO₂ column distributions retrieved from IASI/Metop-B over Etna during 21 consecutive days in March 2021. Etna, one of the most active and best-monitored volcanoes worldwide (Carn et al., 2017; Giammanco et al., 2024), is characterized by frequent degassing and eruptive phases during which SO₂ plumes can rapidly change in strength, spatial extent, and transport pathways, as highlighted by Fig. 16. In such a rapidly evolving context, twice-
 490 daily measurements are essential for capturing the evolution of volcanic gas clouds on short time scales.

Building upon earlier efforts to document volcanic SO₂ variability from space (e.g., Carn et al., 2016, 2017; Fisher et al., 2019; Fioletov et al., 2023), we use this dataset to investigate the variability of volcanic SO₂ emissions over nearly two decades and to characterize the most significant eruptive episodes captured by IASI.

4.1 Consistency between IASI sounders

495 Although the three IASI instruments are identical and have similar equator crossing times, small differences in operational parameters and calibration may lead to discrepancies in retrieved gas abundances, especially for weak absorbers (e.g., Van Damme et al., 2021; Clarisse et al., 2023). Since the first observations from IASI/Metop-B in early 2013, at least two IASI sounders have operated simultaneously, providing several years of overlap that are valuable for assessing their consistency. Notably, with the start of IASI/Metop-C observations in April 2019 and the continued operation of IASI/Metop-A until November
 500 2021, the three IASI sounders operated concurrently for more than two years.

Figure 17a shows the global atmospheric SO₂ mass derived twice daily (morning and evening overpasses) from IASI/Metop-A, -B, and -C measurements, separately, between April 2019 and September 2021. Over this period, three major enhancements of the global SO₂ burden are observed, associated with intense gas emissions from the Raikoke (June 2019), Taal (January 2020), and La Soufrière (April 2021) eruptions. The zoomed views of these events (Fig. 17b–d) show the sharp increase in
 505 atmospheric SO₂ due to each eruption, with the peak SO₂ mass typically reached within 24–48 hours after the onset of the Plinian phase, followed by the characteristic exponential decay of SO₂ in volcanic plumes. In the case of Raikoke (Fig. 17b), one of the major volcanic eruptions over the last decade (e.g., Muser et al., 2020; de Leeuw et al., 2021; Vernier et al., 2024), the decay of the global SO₂ mass is interrupted by several secondary peaks caused by additional SO₂ injections into the atmosphere from the successive eruptions of Ulawun and Manam at the end of June, Ubinas in mid-July, and Ulawun again in
 510 early August.

These zoomed views also highlight the good agreement between the atmospheric SO₂ masses retrieved from the three IASI sounders: for each eruption case, all three instruments capture comparable peak SO₂ burdens, similar decay rates of

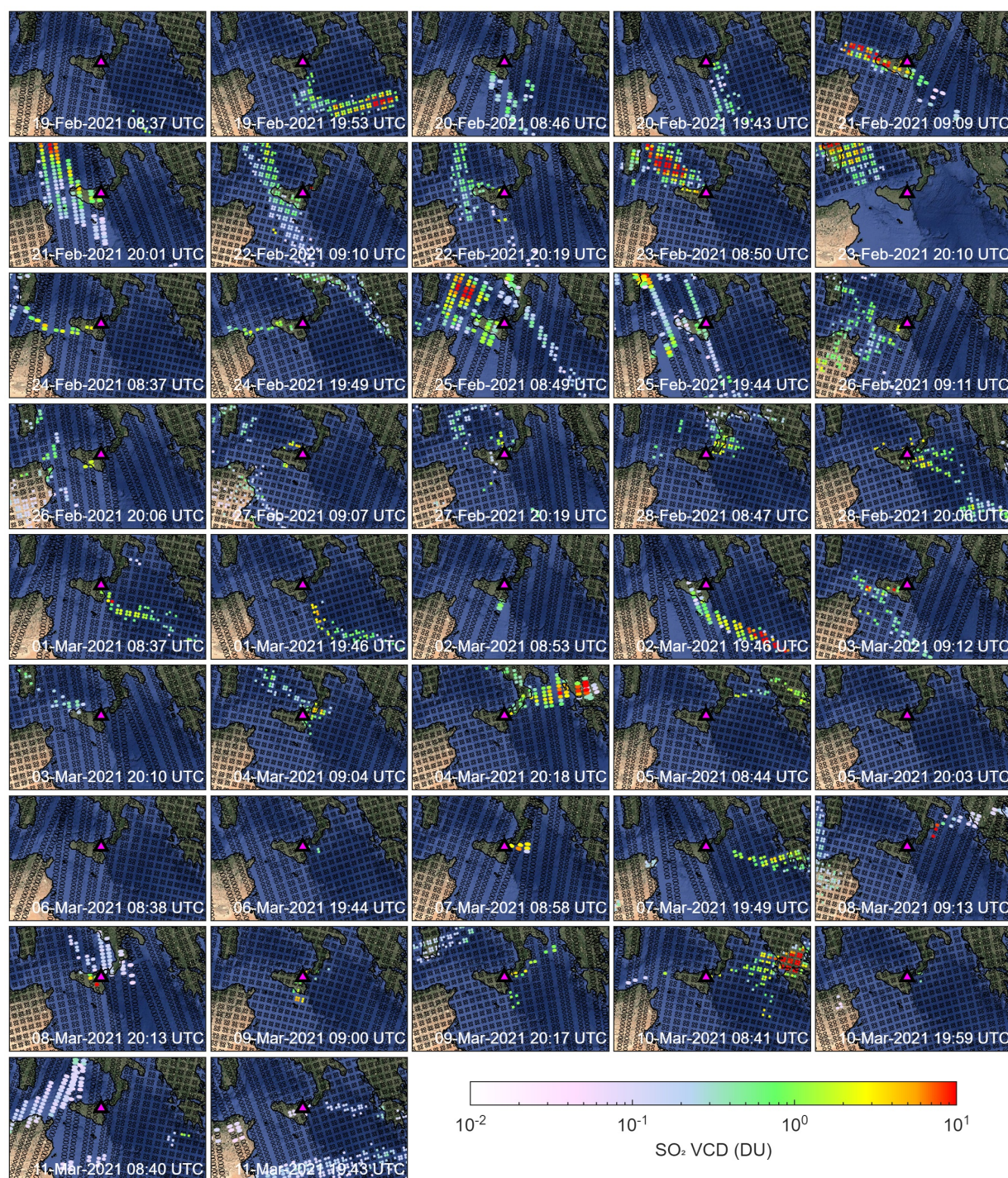


Figure 16. SO₂ VCD (in DU) retrieved from the twice-daily IASI/Metop-B measurements over Etna (triangle) during 21 consecutive days in March 2021. Each dot corresponds to the on-ground footprint of an individual IASI observation. Pixels with no SO₂ detection are displayed as transparent markers with black outlines.

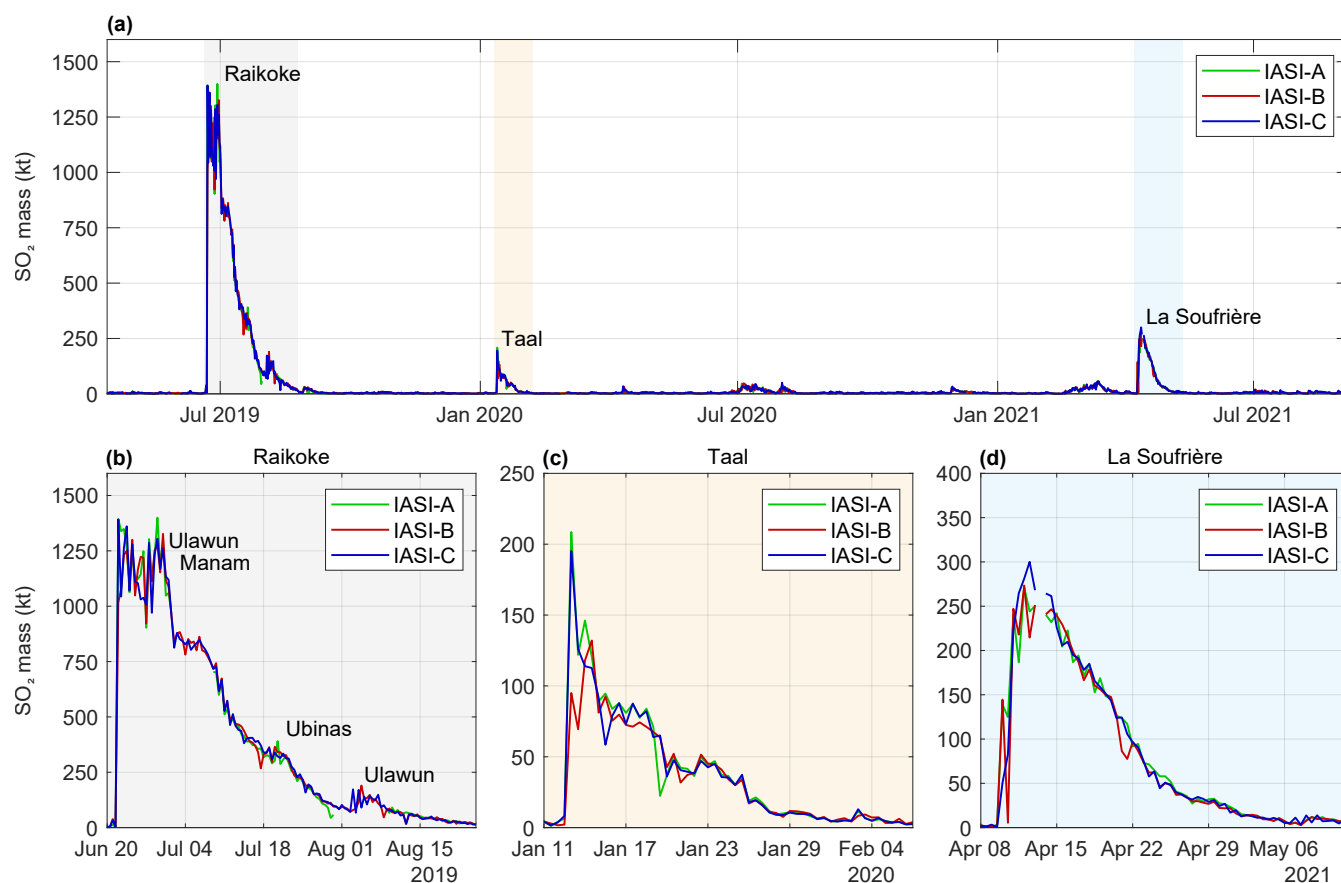


Figure 17. (a) Twice-daily global atmospheric SO₂ mass (in kt) above 5 km altitude derived from IASI/Metop-A (green), -B (red), and -C (blue) observations between April 2019 and September 2021. (b–d) Enlarged views of the three major volcanic eruptions during this period, corresponding to the grey (Raikoke), yellow (Taal), and blue (La Soufrière) shaded areas in a.

the volcanic plumes, and a return to the same background SO₂ levels. This consistency among the three SO₂ datasets is an important prerequisite for the analysis of the entire IASI time series.

515 Nevertheless, in certain individual overpasses, the SO₂ mass derived from one instrument deviates significantly from the other two. This occurs during the Taal eruption, for which IASI/Metop-B does not capture the pronounced SO₂ peak observed by the other sounders, or when IASI/Metop-A shows a drop in SO₂ burden on 19 January 2020. Such discrepancies, which typically affect only single overpasses, are due to the coverage gaps that exist at low latitudes between successive polar orbits of an IASI sounder. Despite the wide IASI across-track swath of ~2200 km, individual orbits from a single satellite do not overlap
 520 in the tropics and leave uncovered longitudinal bands (Clerbaux et al., 2009). As a result, an IASI sounder may detect only part of a volcanic plume and thus underestimate the total atmospheric SO₂ compared with the other sounders that fully sample the plume. These discrepancies occur for eruptions at low latitudes, such as Taal (14° N) and La Soufrière (13° N), but are absent for higher-latitude events like Raikoke (48° N), where consecutive orbits overlap sufficiently. These low-latitude gaps highlight



the advantage of having mutually consistent IASI sounders operating concurrently, as the orbits of one instrument fill the gaps left by another.

4.2 SO₂ total mass time series

In Fig. 18, we present the global atmospheric SO₂ mass time series derived from the entire IASI observational period, considering only SO₂ masses above 5 km altitude to minimize the contribution from anthropogenic sources. Because parts of a volcanic plume may not be fully captured by a single IASI sounder at low latitudes (see Sect. 4.1), only the maximum SO₂ mass among the three IASI sounders (when available) was retained at each time step.

Numerous peaks can be observed throughout the time series, most of which correspond to substantial enhancements in atmospheric SO₂ mass resulting from volcanic eruptions. Using the twice-daily global IASI distributions of SO₂ VCDs to track the origin of the SO₂ plumes, we have identified the erupting volcanoes responsible for all of the large SO₂ mass enhancements as shown in Fig. 18. The most prominent features correspond to Kasatochi (2008), Sarychev Peak (2009), Grímsvötn (2011), Puyehue (2011), Nabro (2011), Calbuco (2015), and Raikoke (2019). Other important events include, e.g., the Merapi (2010), Copahue (2012), Ambae (2018), Taal (2020), La Soufrière (2021), Hunga Tonga (2022), Mauna Loa (2022), Sheveluch (2023), and Ruang (2024) eruptions. The years 2016–2017 in the IASI record are marked by less frequent and overall lower volcanic SO₂ masses, with the exception of the 2016 Pavlof eruption. The first major event detected by IASI was the eruption of Jebel at Tair (Yemen), a stratovolcano located in the Red Sea, on 30 September 2007. This event was studied in detail by Clarisse et al. (2008) with IASI and Eckhardt et al. (2008) with other sounders. The most recent major event up to the end of 2025 is the eruption of Hayli Gubbi (Ethiopia), a shield volcano in the East African Rift Zone, on 23 November 2025. This event, which generated a large SO₂ plume that drifted across the Middle East and reached China in the following days, marked the first explosive eruption ever recorded for this volcano. Among the SO₂ peaks of lower intensity, many are attributed to volcanoes known for their persistent or frequent activity, and in some cases, continuous degassing over the IASI observation period. Examples include Etna, Popocatepetl, Ubina, and Nyamuragira. Over the last three years (2023–2025), volcanoes showing frequent SO₂ emissions captured by IASI also include Sheveluch, Reykjanes, Lewotobi, and Kīlauea.

Another notable feature in Fig. 18 is the presence of numerous small peaks (typically of SO₂ masses below 30 kt), mostly during the early years of the IASI record. While some of these peaks are attributed to small volcanic eruptions (not shown in Fig. 18 for clarity), many correspond to enhanced atmospheric SO₂ masses above 5 km altitude originating from significant anthropogenic emissions, particularly from eastern Asia. Indeed, previous studies have shown that anthropogenic SO₂ can be transported over long distances and can reach high altitudes (e.g., van Donkelaar et al., 2008; Clarisse et al., 2011; Fadnavis et al., 2019). The frequency and intensity of these non-volcanic peaks gradually decrease over the IASI record, consistent with the substantial reduction of anthropogenic SO₂ emissions in China following the implementation of strict national air-quality controls in the early 2010s (Krotkov et al., 2016; Zheng et al., 2018; Fioletov et al., 2023). After 2014–2015, such anthropogenic SO₂ events are largely absent from the record (Fig. 18).

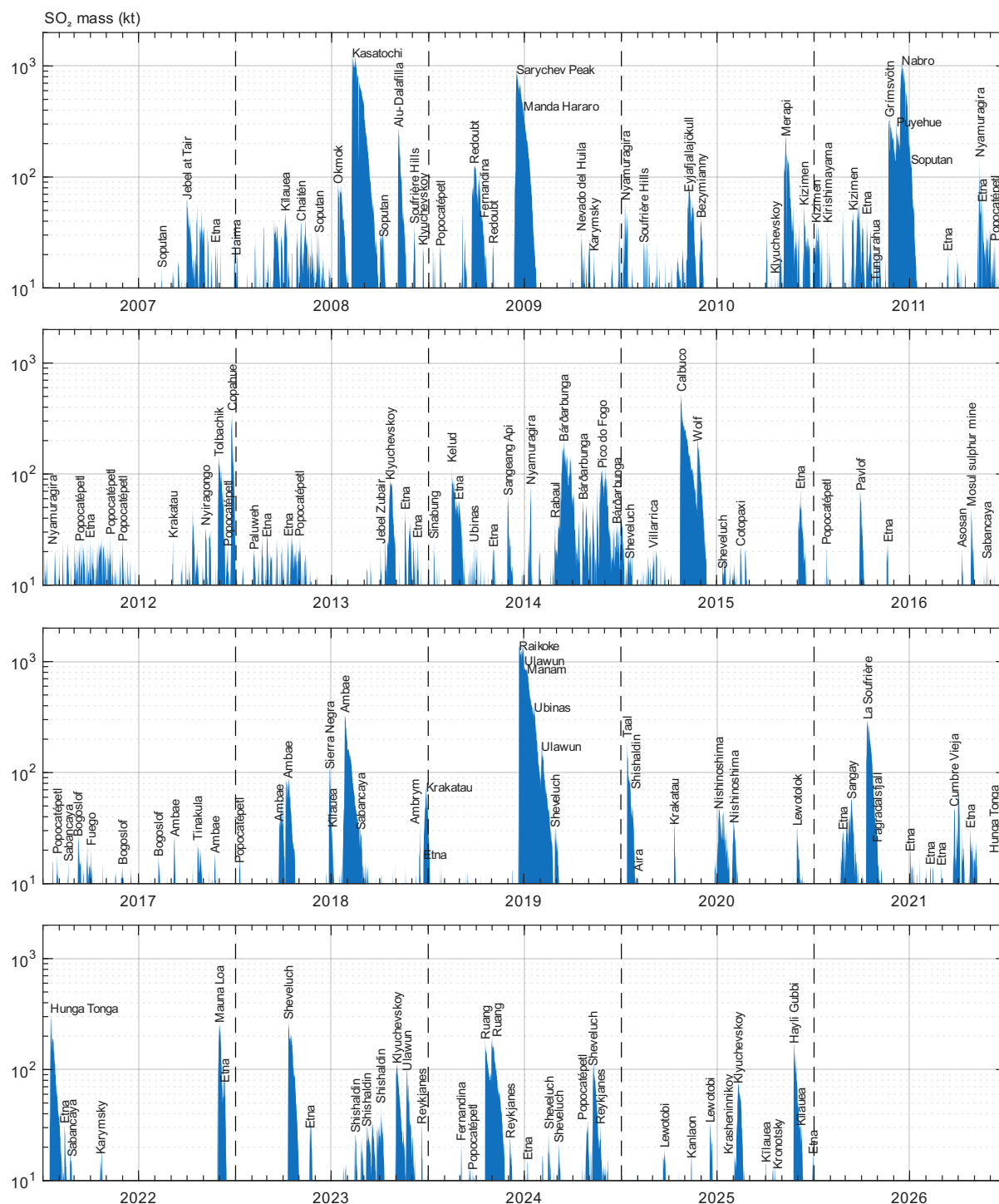


Figure 18. Twice-daily global atmospheric SO₂ masses (in kt) above 5 km altitude derived from IASI observations between July 2007 and December 2025. At each time step, only the maximum SO₂ mass between IASI/Metop-A, -B, and -C (when available) was retained. Major volcanic eruptions detectable with the IASI SO₂ product are indicated (non-exhaustive list).

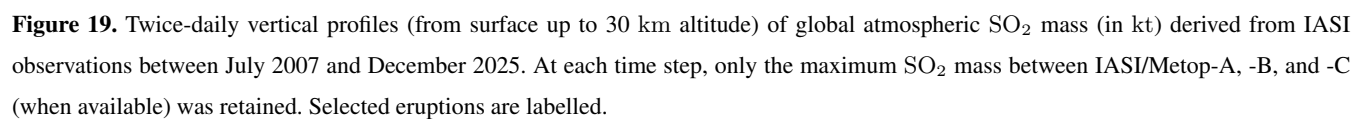


4.3 SO₂ mass profile time series

Figure 19 presents the time series of SO₂ mass profiles from the surface up to 30 km altitude retrieved from IASI, i.e., at each time step, the vertical distribution of the global mass according to the retrieved altitude of SO₂. Similar to Fig. 18, a selection of volcanic eruptions identifiable with IASI is highlighted in Fig. 19. For instance, the major events previously discussed (Kasatochi, Sarychev Peak, Grímsvötn – Puyehue – Nabro, Calbuco, and Raikoke) are immediately recognizable due to the exceptionally large SO₂ masses they emitted.

The most interesting feature revealed by Fig. 19 is the clear contrast in the vertical distribution of SO₂ masses originating from major inter- and extratropical eruptions, consistent with previous studies (e.g., Robock, 2000; Clarisse et al., 2012; Theys et al., 2013; Carboni et al., 2016; Carn et al., 2016). Within the tropics, SO₂ masses frequently reach higher altitudes (up to 18–19 km), reflecting the elevated tropical tropopause. Although part of the emitted mass also remains in the free troposphere, the bulk is often detected near or at the tropopause. Typical examples in the IASI record are Alu-Dalafilla (2008), Merapi (2010), Kelud (2014), Wolf (2015), Ambae (2018), La Soufrière (2021), and Ruang (2024). Even eruptions with comparatively smaller SO₂ emissions can reach such altitudes, such as Soufrière Hills (2010), Sangeang Api (2014), Lewotolok (2020), and Lewotobi (2025). In contrast, eruptions at mid- and high latitudes typically inject SO₂ to lower altitudes, rarely exceeding 13–14 km, due to the lower regional tropopause. This is the case for most events in the North Pacific (e.g., 2009 Redoubt, 2012 Tolbachik, and 2023 Sheveluch), Iceland (e.g., 2010 Eyjafjallajökull, 2011 Grímsvötn), and the Southern Andes (e.g., 2011 Puyehue, 2012 Copahue).

This pattern, however, is not systematic, as the SO₂ injection height depends on various parameters (Robock, 2000; Textor et al., 2003), such as the type of eruption (Plinian eruptions vs. effusive or less explosive eruptions), the atmospheric structure, the plume thermal buoyancy, or the timing of SO₂ degassing (during or following the main blast). For example, sustained lava flows and high SO₂ degassing rates during the prolonged 2014 Bárðarbunga (Holuhraun) effusive fissure eruption in Iceland generated multiple gas plumes that remained largely confined below 9 km (Pedersen et al., 2017; Simmons et al., 2017). Similarly, several SO₂ plumes from major tropical eruptions did not reach the tropopause, with most of their mass remaining in the free troposphere. For instance, although the large eruption of Mauna Loa (a basaltic shield volcano) of December 2022 produced SO₂ reaching 16–17 km altitude after atmospheric transport, Fig. 19 indicates that the majority of the mass remained below 10 km. Other examples include the 2008 Kīlauea, 2009 Nevado del Huila, and 2012 Nyiragongo eruptions, whose SO₂ plumes did not exceed 12–13 km. Conversely, eruptions with a strong Plinian phase at mid- and high-latitudes may inject substantial SO₂ amounts well above the regional tropopause into the lower stratosphere (e.g., Textor et al., 2003; Krotkov et al., 2010; Kremser et al., 2016). The IASI record clearly shows that this occurred during the 2008 Kasatochi, 2009 Sarychev Peak, and 2019 Raikoke eruptions: the initial explosive phase generated large SO₂ plumes reaching up to 20 km, directly followed by masses injected at lower altitudes, with the bulk eventually capped near the tropopause (12–13 km). A similar pattern is observed in Fig. 19 at intertropical latitudes for the 2022 Hunga Tonga eruption. As discussed in Sect. 2.3.6, IASI detected an initial injection exceeding 30 km, while subsequent, larger SO₂ masses were confined between 16 and 18 km, consistent with the regional tropopause height.





590 In contrast to Fig. 18, Fig. 19 displays the SO₂ mass profile down to the surface, thereby revealing an atmospheric back-
 ground of SO₂ predominantly located in the 1–5 km altitude range. Although volcanic eruptions can contribute to this back-
 ground, it is largely driven by SO₂ emissions from anthropogenic activities, such as smelters, coal-fired power plants, and other
 industrial and domestic sources (McLinden et al., 2016; Crippa et al., 2018; Fioletov et al., 2023). As mentioned in Sect. 4.2,
 under specific conditions, concentrated plumes of anthropogenic pollutants can reach the free troposphere, as exemplified in
 595 Fig. 19 by the non-volcanic SO₂ mass peaks up to 10–12 km observed in the first years of the IASI time series. Another
 example is the large SO₂ release from the fire at the Al-Mishraq sulphur plant (near Mosul, Iraq) in October 2016 (Björnham
 et al., 2017), which is clearly visible in Fig. 19.

The background SO₂ exhibits a clear seasonal cycle in the IASI record: although it generally resides between 1 and 5 km,
 substantial SO₂ masses are also detected close to the surface during Northern Hemisphere winter. This results from enhanced
 600 anthropogenic emissions during the cold season in major source regions at mid- and high-latitudes, such as eastern China
 and Norilsk, Russia (Bauduin et al., 2014; Crippa et al., 2018; Fioletov et al., 2023), combined with an extended atmospheric
 lifetime of SO₂ and a lower planetary boundary layer, which often confines the anthropogenic pollutants near the surface.
 Although this seasonal pattern persists throughout the time series, Fig. 19 also reveals a decrease in background SO₂ mass
 after 2014–2015. As discussed in Sect. 4.2, this results mostly from the substantial reductions in anthropogenic SO₂ emissions
 605 in China since the early 2010s.

4.4 Major eruptions

In Table 2, we list all major volcanic eruptions detected with IASI between July 2007 and December 2025. These were
 identified through a systematic analysis of the data, flagging all instances where the retrieved SO₂ mass exceeded 30 kt
 within any 45° latitude × 90° longitude region. A maximum SO₂ mass and date were then associated with each eruption,
 610 corresponding to the largest value measured in a single overpass by a single IASI sounder within 72 hours of the eruption
 onset. These selection criteria were designed to exclude aged plumes and to avoid selecting spatially extended plumes resulting
 from multiple successive emission events. However, we do not report all detected events from volcanoes exhibiting sustained
 or quasi-continuous eruptive activity over long periods. For example, the Bárðarbunga eruption lasted from August 2014
 to February 2015 (Schmidt et al., 2015; Gauthier et al., 2016), and Nishinoshima remained active from December 2019 to
 615 September 2020, with a peak activity in July 2020 (Kaneko et al., 2022). During these episodes, IASI detected numerous fresh
 SO₂ plumes exceeding the 30 kt threshold. In such instances, only the most significant events are listed in Table 2.

Figure 20 shows, for each volcano listed in Table 2, the maximum SO₂ mass measured by IASI, with circle sizes proportional
 to the SO₂ mass. It is important to note that this SO₂ quantity represents the instantaneous atmospheric mass at the time of
 an IASI overpass. Consequently, it can differ significantly from the total SO₂ mass emitted over the entire eruption event and
 620 from the daily SO₂ emission fluxes often reported in the literature, which are typically derived from satellite data using specific
 techniques or modelling approaches (e.g., Theys et al., 2013; Carn et al., 2017; Esse et al., 2025). For many of the events listed
 in Table 2, the IASI-derived SO₂ mass is compared with the same type of atmospheric mass estimates obtained from various
 satellite sensors and reported in the literature (non-exhaustive list). For each eruption, we also provide the IASI-based SO₂

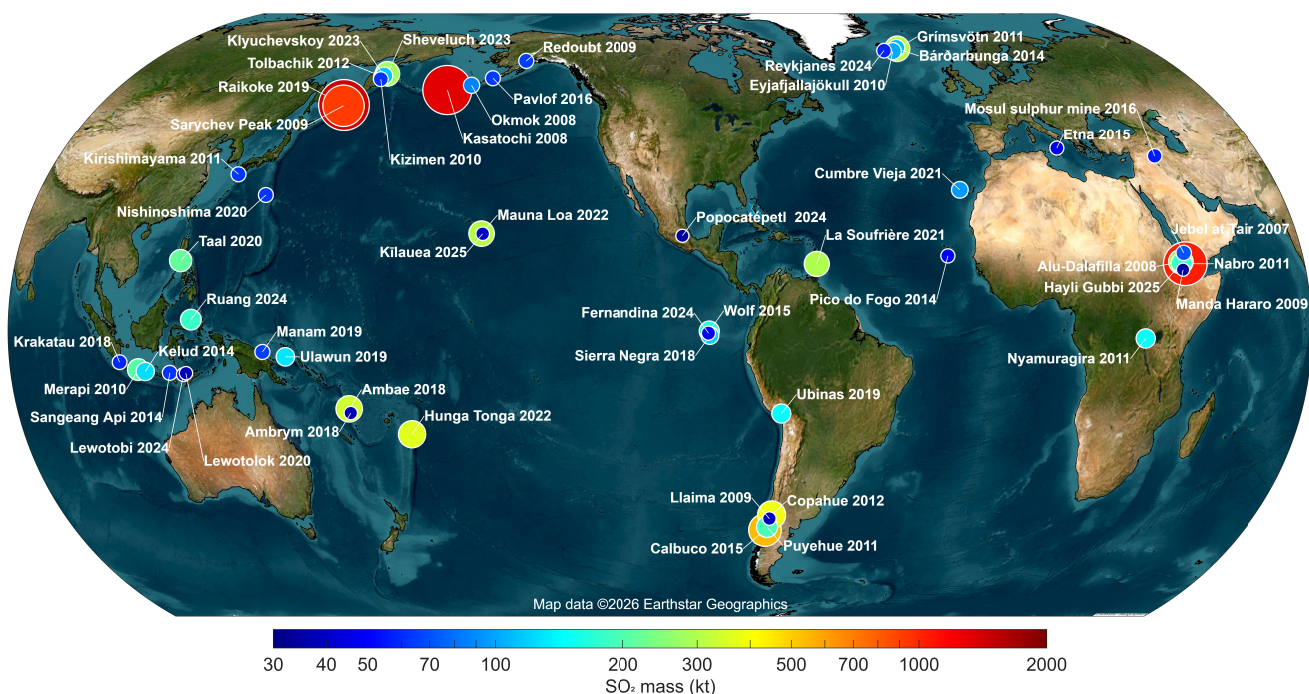


Figure 20. Map of major volcanic eruptions detected by IASI between July 2007 and December 2025 for which an instantaneous atmospheric SO_2 mass above 30 kt was derived (see Table 2). When multiple eruptions were detected by IASI for the same volcano, only the event with the largest retrieved SO_2 mass has been retained. Each circle is colour-coded according to the detected SO_2 mass, with its size proportional to that mass. Map data from Earthstar Geographics (2026).

masses below and above 8 km altitude, the lower and upper bounds of the narrowest altitude range containing 75% of the total SO_2 mass, and the altitude of the SO_2 mass peak.

In terms of atmospheric SO_2 mass, and based on our measurement criteria, three of the four largest eruptions detected by IASI originate from volcanoes in the North Pacific: Raikoke (2019; 1409 kt) and Sarychev Peak (2009; 912 kt) in the Kuril volcanic arc, and Kasatochi (2008; 1309 kt) in the Aleutian arc (Fig. 20). For each of these events, the mass estimates derived in the present work fall well within the ranges reported in previous studies based on IASI and on other IR and UV-Vis sensors (see references in Table 2). Notably, the agreement between IASI, TROPOMI, and OMPS mass estimates for Raikoke is particularly strong, with studies reporting values close to 1400 kt (Muser et al., 2020; Gorkavyi et al., 2021; de Leeuw et al., 2021; McKee et al., 2021a; Inness et al., 2022; Vernier et al., 2024).

The other major eruption in the IASI record is the 2011 Nabro event, in the Afar Rift volcanic province (Clarisse et al., 2014). In Table 2, we provide IASI-based SO_2 masses for both 15 June (734 kt) and 16 June (1029 kt) 2011, due to the



635 marked shift in the altitude range containing 75% of the total mass. On 15 June, most of the SO₂ from the initial explosive phase was located between 9 and 18 km altitude, with a mass peak at 17 km, consistent with Fromm et al. (2014). On 16 June, IASI detected a second, lower-altitude injection, which shifted the altitude band containing 75% of the total mass downward to 5–13 km.

Another noticeable eruption is that of Calbuco in 2015 (546 kt), in the Southern Andean arc, with the bulk of the mass
 640 contained between 15 and 17 km. For this event, the SO₂ mass derived is slightly higher than previous estimates (Venzke, 2015; Bègue et al., 2017; Pardini et al., 2018; Baray et al., 2025). Interestingly, the other two major eruptions detected by IASI in this region, those of Puyehue (2011; 192 kt) and Copahue (2012; 387 kt), yielded SO₂ masses located at comparatively lower altitudes (9–12 km and 4–8 km, respectively) than Calbuco.

Although one of the most powerful explosive eruptions of the satellite era, the January 2022 Hunga Tonga eruption produced
 645 a modest maximum of 358 kt of atmospheric SO₂ as measured by IASI. This value is significantly lower than those obtained for the largest eruptions reported in this study (Raikoke, Kasatochi, Nabro, and Sarychev Peak), but similar to the masses derived for, e.g., Ambae (2018; 336 kt), Mauna Loa (2022; 308 kt) and Copahue (2012; 387 kt). The SO₂ mass retrieved in this study is consistent with estimates from other satellite sensors such as CrIS, TROPOMI, and OMPS (e.g., Carn et al., 2022; Zhu et al., 2022; Sadeghi et al., 2025), as summarized in Table 2, although some studies report significantly higher values
 650 (e.g., Xia et al., 2024; Sellitto et al., 2024). Among other factors, the difficulty of retrieval algorithms in constraining the high altitudes reached by the Hunga Tonga SO₂ plume following the initial explosion contributes to the discrepancies between these mass estimates. In the present study, 75% of the entire SO₂ mass from the initial phase is contained within 17–29 km, with a mass peak at 27 km (see Fig. 8).



Table 2: Maximum atmospheric SO₂ masses (in kt) derived from IASI observations for major volcanic eruptions between July 2007 and December 2025, along with the corresponding measurement dates. Only eruptions with SO₂ masses exceeding 30 kt within 72 hours of eruption onset are reported. Values in parentheses indicate the SO₂ mass below and above 8 km altitude, respectively. The lower and upper bounds (in km) of the narrowest altitude range containing 75% of the total SO₂ mass, as well as the altitude of the SO₂ mass peak (in parentheses), are provided. Other satellite-derived SO₂ mass estimates found in the literature are listed with their corresponding references (non-exhaustive).

Date	Volcano	Present study		Other satellite observations			Reference(s)
		SO ₂ mass (kt)	Altitude (km)	Mass (kt)	Sensor		
01.10.2007	Jebel at Tair	71 (25+46)	3–16 (16)	46	IASI		Clarisse et al. (2008)
				100–120	AIRS/OMI/SEVIRI		Eckhardt et al. (2008)
13.07.2008	Okmok	87 (3+84)	10–12 (12)	90–100	IASI		Carn et al. (2016)
				60–70	IASI		Carboni et al. (2016)
				200–300	AIRS		Prata et al. (2010); Carn et al. (2016)
				100–200	OMI		Spinei et al. (2010)
09.08.2008	Kasatochi	1309 (2+1307)	11–15 (15)	1600–1700	IASI		Karagulian et al. (2010); Clarisse et al. (2012); Carn et al. (2016)
				900	IASI		Carboni et al. (2016)
				1100–1200	AIRS		Prata et al. (2010)
				1200–2000	OMI		Krotkov et al. (2010); Theys et al. (2015); Yang et al. (2010); Li et al. (2017)
				1600–2500	GOME-2		Richter et al. (2009); Nowlan et al. (2011)
				1200–2700	MODIS		Corradini et al. (2010)
05.11.2008	Alu-Dalafilla	282 (85+197)	6–15 (15)	200–300	IASI		Carn et al. (2016)
				100–200	IASI/OMI		Carboni et al. (2016)
				100–200	AIRS		Carn et al. (2016)
24.03.2009	Redoubt	66 (7+59)	8–12 (12)	100–150	IASI		Carn et al. (2016)
				100–200	AIRS		Carn et al. (2016)
				60	OMI		Lopez et al. (2013)
05.04.2009	Redoubt	48 (13+35)	5–12 (11)	24	OMI		Lopez et al. (2013)
07.04.2009	Llaima	39 (39+0)	2–5 (4)				
13.04.2009	Fernandina	35 (35+0)	2–3 (3)	147	OMI		Wunderman (2009)
16.06.2009	Sarychev Peak	912 (24+888)	9–15 (12)	900–1200	IASI		Clarisse et al. (2012); Jégou et al. (2013)
				600–700	IASI		Carboni et al. (2016)
				1000–1100	AIRS		Carn et al. (2016)
				950–1200	OMI		Carn et al. (2013); Theys et al. (2015); Carn et al. (2016)
29.06.2009	Manda Hararo	35 (24+11)	2–12 (4)	34	OMI		Ferguson et al. (2010)
09.01.2010	Nyamuragira	73 (58+15)	4–7 (6)	20	IASI		Carn et al. (2016)
08.05.2010	Eyjafjallajökull	102 (90+12)	2–7 (4)	60–70	IASI		Carn et al. (2016)
				180	IASI		Carboni et al. (2016)
				120–140	GOME-2		Rix et al. (2012)
				70	OMI		Thomas and Prata (2011)
				20–30	AIRS		Thomas and Prata (2011)
				56–62	MODIS		Pugnaghi et al. (2016)
15.05.2010	Eyjafjallajökull	50 (33+17)	5–9 (6)	70	IASI		Carboni et al. (2012)
				80–90	GOME-2		Rix et al. (2012)
				30–40	AIRS/OMI		Thomas and Prata (2011)

Continued on next page



Table 2 – continued from previous page

Date	Volcano	Present study		Other satellite observations		Reference(s)
		SO ₂ mass (kt)	Altitude (km)	Mass (kt)	Sensor	
08.11.2010	Merapi	205 (9+196)	12–16 (16)	200–250	AIRS/IASI	Carboni et al. (2016); Carn et al. (2016)
				227	OMI	Wunderman (2011)
13.12.2010	Kizimen	62 (16+46)	6–10 (10)	30–40	AIRS/IASI	Carn et al. (2016)
31.12.2010	Kizimen	33 (15+18)	3–10 (8)	20–25	IASI	Carn et al. (2016)
27.01.2011	Kirishimayama	63 (63+0)	2–5 (4)	30–40	AIRS/IASI	Carn et al. (2016)
14.03.2011	Kizimen	62 (57+5)	2–7 (5)			
23.05.2011	Grímsvötn	307 (8+299)	7–10 (9)	320–350	IASI	Clarisse et al. (2012); Carn et al. (2016); Prata et al. (2017)
				700–800	IASI	Carboni et al. (2016)
				720	AIRS	Carn et al. (2016)
				230–240	AIRS/GOME-2	Prata et al. (2017)
				290–300	OMI	Sigmarsson et al. (2013); Ge et al. (2016); Prata et al. (2017)
06.06.2011	Puyehue	192 (0+192)	9–12 (12)	180–250	IASI	Clarisse et al. (2012); Theys et al. (2013); Carn et al. (2016)
				300–400	IASI	Carboni et al. (2016)
				260	AIRS	Carn et al. (2016)
15.06.2011	Nabro	734 (107+627)	9–18 (17)			
16.06.2011	Nabro	1029 (296+733)	5–13 (10)	1000–1100	AIRS/IASI	Clarisse et al. (2012, 2014); Carn et al. (2016)
				1600	IASI	Carboni et al. (2016)
				2000	OMI	Ge et al. (2016)
				1500	GOME-2	Theys et al. (2013)
10.07.2011	Nabro	44 (30+14)	2–12 (5)			
11.11.2011	Nyamuragira	148 (28+120)	7–10 (9)	150–200	IASI	Carn et al. (2016)
				90–100	AIRS	Carn et al. (2016)
				120–180	OMI	Theys et al. (2013)
27.11.2011	Nyamuragira	31 (16+15)	4–11 (6)	15	IASI	Carn et al. (2016)
				20–30	OMI	Theys et al. (2013)
29.11.2012	Tolbachik	113 (97+16)	4–8 (6)	90–100	IASI	Carn et al. (2016)
				150–200	AIRS	Carn et al. (2016)
				40	AIRS	Telling et al. (2015)
				5–10	OMI/OMPS	Telling et al. (2015)
24.12.2012	Copahue	387 (293+94)	4–8 (6)	450–500	IASI	Carn et al. (2016)
				700	IASI	Carboni et al. (2016)
				150–200	AIRS	Carn et al. (2016)
20.10.2013	Klyuchevskoy	72 (40+32)	5–9 (8)	50	IASI	Carn et al. (2016)
14.02.2014	Kelud	126 (2+124)	16–18 (17)	100–150	IASI	Carn et al. (2016)
				180–190	IASI	Zhu et al. (2020)
				250	AIRS	Carn et al. (2016)
				170–180	AIRS	Zhu et al. (2020)
				110–200	OMI	Carn et al. (2016); Li et al. (2017); Zhu et al. (2020)
				179	OMPS	Li et al. (2017)
31.05.2014	Sangeang Api	63 (16+47)	7–17 (17)	60–70	IASI	Carn et al. (2016)
				100	AIRS	Carn et al. (2016)
01.07.2014	Nyamuragira	31 (31+0)	3–4 (4)			
14.07.2014	Nyamuragira	105 (104+1)	3–5 (5)			
28.07.2014	Nyamuragira	30 (30+0)	3–5 (4)			
04.09.2014	Bárðarbunga	111 (111+0)	2–5 (4)	70	IASI	Carn et al. (2016)

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Table 2 – continued from previous page

Date	Volcano	Present study		Other satellite observations		Reference(s)
		SO ₂ mass (kt)	Altitude (km)	Mass (kt)	Sensor	
				180–260	IASI	Carboni et al. (2019)
				170–180	IASI/OMI	Schmidt et al. (2015)
				226	SEVIRI	Gauthier et al. (2016)
08.09.2014	Nyamuragira	82 (78+4)	4–6 (5)			
21.09.2014	Bárðarbunga	100 (97+3)	1–4 (3)	180–260	IASI	Carboni et al. (2019)
				60–120	IASI/OMI	Schmidt et al. (2015)
				90–100	SEVIRI	Gauthier et al. (2016)
13.10.2014	Bárðarbunga	91 (91+0)	2–4 (3)	40	IASI	Carn et al. (2016)
				100–150	IASI	Carboni et al. (2019)
				100	SEVIRI	Gauthier et al. (2016)
28.10.2014	Bárðarbunga	102 (102+0)	1–4 (3)	120–180	IASI	Carboni et al. (2019)
				20	SEVIRI	Gauthier et al. (2016)
10.11.2014	Bárðarbunga	59 (59+0)	1–3 (2)	40–50	IASI	Carn et al. (2016)
				60–120	IASI	Carboni et al. (2019)
				20–30	SEVIRI	Gauthier et al. (2016)
27.11.2014	Pico do Fogo	50 (49+1)	1–4 (3)	30–40	IASI	Carn et al. (2016)
				25	OMI	Wunderman (2014)
02.12.2014	Bárðarbunga	45 (42+3)	1–6 (5)	100–140	IASI	Carboni et al. (2019)
23.12.2014	Bárðarbunga	41 (40+1)	1–6 (5)	15	IASI	Carn et al. (2016)
				40–60	IASI	Carboni et al. (2019)
25.04.2015	Calbuco	546 (3+543)	15–17 (17)	370–410	IASI	Bègue et al. (2017); Baray et al. (2025)
				300–400	AIRS/OMPS/OMI	Venzke (2015)
				300	GOME-2	Pardini et al. (2018)
26.05.2015	Wolf	168 (34+134)	8–16 (14)	130	IASI	Bègue et al. (2017)
				118	OMI	Crafford and Venzke (2016)
05.12.2015	Etna	47 (9+38)	5–13 (12)	5–10	OMI	D’Aleo et al. (2019)
30.03.2016	Pavlof	64 (61+3)	5–7 (6)	33	AIRS	Marshak et al. (2018)
				18	OMI	Crafford and Venzke (2017)
				25	EPIC	Marshak et al. (2018)
21.05.2016	Etna	34 (34+0)	2–6 (5)			
05.09.2017	Fernandina	37 (37+0)	3–5 (4)	8	OMPS	Vasconez et al. (2018)
27.03.2018	Ambae	55 (21+34)	5–15 (6)	150	OMI/OMPS	Malinina et al. (2021)
				80	OMI	Bani et al. (2025)
10.04.2018	Ambae	81 (19+62)	7–17 (17)	123	OMI	Crafford and Venzke (2018)
				120–180	OMI/OMPS	Malinina et al. (2021)
				101	OMI	Bani et al. (2025)
28.06.2018	Sierra Negra	118 (89+29)	3–8 (8)	50	OMI/OMPS	Vasconez et al. (2018)
				55	EPIC	Carn et al. (2018)
27.07.2018	Ambae	336 (46+290)	13–16 (15)	540	OMI/OMPS	Malinina et al. (2021)
				350–390	TROPOMI	Malinina et al. (2021); Liu et al. (2023); Bani et al. (2025)
				233	OMI	Krippner and Venzke (2019a)
15.12.2018	Ambrym	38 (38+0)	1–6 (6)	23	OMI	Krippner and Venzke (2019b)
				52–55	TROPOMI	Shreve et al. (2019)
28.12.2018	Krakatau	59 (3+56)	12–16 (14)	40–55	multi-sensors	Prata et al. (2020)
				50	OMI/OMPS	Gouhier and Paris (2019)
29.12.2018	Etna	36 (36+0)	1–4 (4)	9–26	multi-sensors	Corradini et al. (2021)
22.06.2019	Raikoke	1409 (34+1375)	12–17 (15)	1400	IASI	Vernier et al. (2024)

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Table 2 – continued from previous page

Date	Volcano	Present study		Other satellite observations		
		SO ₂ mass (kt)	Altitude (km)	Mass (kt)	Sensor	Reference(s)
				1100	CrIS	Hyman and Pavolonis (2020)
				1400	TROPOMI	Muser et al. (2020); de Leeuw et al. (2021); McKee et al. (2021a)
				1200–1600	TROPOMI	Inness et al. (2022)
				900–1000	GOME-2	Inness et al. (2022)
				1300–1400	OMPS	Gorkavyi et al. (2021)
				1000–2000	HIMAWARI	Muser et al. (2020); Vernier et al. (2024)
26.06.2019	Ulawun	93 (0+93)	15–17 (16)	83	IASI	Fabris et al. (2025)
				90–121	TROPOMI	Fabris et al. (2025)
				136	TROPOMI	McKee et al. (2021b)
27.06.2019	Manam	65 (0+65)	15–17 (17)	58	TROPOMI	Cotterill et al. (2024)
20.07.2019	Ubina	144 (4+140)	11–14 (13)			
04.08.2019	Ulawun	131 (0+131)	15–17 (16)	189	TROPOMI	McKee et al. (2021b)
13.01.2020	Taal	218 (33+185)	10–17 (14)			
04.07.2020	Nishinoshima	51 (43+8)	4–8 (6)	50	OMPS/TROPOMI	Kaneko et al. (2022)
				73	TROPOMI	Crafford and Venzke (2020)
11.07.2020	Nishinoshima	52 (51+1)	4–7 (6)	60–100	OMPS/TROPOMI	Kaneko et al. (2022)
				74	TROPOMI	Crafford and Venzke (2020)
01.08.2020	Nishinoshima	63 (63+0)	4–6 (6)	75–85	OMPS/TROPOMI	Kaneko et al. (2022)
				50	TROPOMI	Crafford and Venzke (2020)
29.11.2020	Lewotolok	37 (18+19)	3–16 (4)	38	TROPOMI	Bennis and Venzke (2021)
12.04.2021	La Soufrière	296 (1+295)	13–17 (16)	310	IASI	Taylor et al. (2023)
				310	TROPOMI	Esse et al. (2023)
03.10.2021	Cumbre Vieja	95 (95+0)	3–4 (4)	75	TROPOMI	Milford et al. (2023)
				85–90	TROPOMI	Filonchuk et al. (2022)
09.10.2021	Cumbre Vieja	54 (54+0)	2–5 (5)	50–60	TROPOMI	Filonchuk et al. (2022); Milford et al. (2023)
19.10.2021	Cumbre Vieja	59 (59+0)	3–4 (4)	70	TROPOMI	Milford et al. (2023)
08.01.2022	Wolf	37 (37+0)	2–4 (4)	60	TROPOMI	Crafford and Venzke (2022)
15.01.2022	Hunga Tonga	358 (0+358)	17–29 (27)	1000	IASI	Sellitto et al. (2024)
				400	CrIS	Sadeghi et al. (2025)
				400	TROPOMI	Carn et al. (2022)
				300–320	TROPOMI	Zhu et al. (2022)
				572–794	TROPOMI	Xia et al. (2024)
				300–320	OMPS	Zhu et al. (2022)
				380–420	OMPS	Carn et al. (2022); Xia et al. (2024)
				220	EPIC	Carn et al. (2022)
				652–809	EMI-2	Xia et al. (2024)
02.12.2022	Mauna Loa	308 (297+11)	3–6 (5)	160	TROPOMI	Esse et al. (2025)
10.12.2022	Mauna Loa	95 (67+28)	3–9 (6)			
11.04.2023	Sheveluch	281 (22+259)	7–11 (9)	215–244	IASI	Girina et al. (2023)
				215	TROPOMI	Bennis (2023)
02.11.2023	Klyuchevskoy	113 (6+107)	8–11 (11)			
21.11.2023	Ulawun	99 (4+95)	11–16 (15)			
22.12.2023	Reykjanes	38 (38+0)	2–4 (4)			
08.02.2024	Reykjanes	33 (33+0)	1–3 (3)			
04.03.2024	Fernandina	49 (48+1)	2–5 (5)	46	TROPOMI	Sennert (2024)
18.04.2024	Ruang	181 (0+181)	16–18 (18)	190–210	HIRAS/HIRAS-II	Zeng et al. (2025)

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Date	Volcano	Present study		Other satellite observations		Reference(s)
		SO ₂ mass (kt)	Altitude (km)	Mass (kt)	Sensor	
				230	TROPOMI	Zeng et al. (2025)
				161–185	TROPOMI	Fabris et al. (2025)
01.05.2024	Ruang	143 (0+143)	14–18 (17)	135–151	TROPOMI	Fabris et al. (2025)
18.08.2024	Sheveluch	31 (29+2)	2–7 (3)			
24.08.2024	Reykjanes	35 (35+0)	1–3 (2)			
30.10.2024	Popocatepetl	34 (34+0)	4–6 (5)			
08.11.2024	Sheveluch	79 (29+50)	6–11 (10)			
09.11.2024	Lewotobi	47 (0+47)	15–17 (16)			
21.11.2024	Reykjanes	58 (57+1)	2–4 (3)			
18.06.2025	Lewotobi	34 (6+28)	9–16 (16)			
10.08.2025	Klyuchevskoy	62 (10+52)	7–11 (11)			
19.10.2025	Kilauea	40 (38+2)	2–5 (4)			
24.11.2025	Hayli Gubbi	181 (16+165)	10–16 (12)			

655 5 Conclusions

In this work, we presented a new algorithm for the fast, simultaneous retrieval of atmospheric SO₂ plume altitudes and column abundances from twice-daily, global IASI measurements. Building upon earlier developments, the algorithm brings together several methodological advances that provide improved performance and accuracy across a wide range of atmospheric conditions. In particular, the algorithm shows enhanced sensitivity to weak SO₂ signals and low-altitude plumes, while also providing robust retrievals for dense and optically thick volcanic plumes. The best performance is achieved for plumes located above 8 km, with uncertainties gradually increasing toward the lower troposphere and in the presence of high H₂O content. The retrieved SO₂ altitudes show good agreement with CALIOP lidar measurements, typically within 1–2 km for fresh and moderately aged volcanic plumes. In the lower stratosphere, the algorithm tends to underestimate the altitude of slowly ascending, aged plumes. Nevertheless, the algorithm demonstrates strong capability to retrieve plume altitudes well above the tropical tropopause (up to 36 km; see Fig. 7) in the aftermath of the 2022 Hunga Tonga eruption, in good agreement with CALIOP and independent observations. Comparisons of SO₂ columns with TROPOMI in fresh volcanic plumes show overall satisfactory agreement, particularly in light of the challenges associated with SO₂ retrievals. Remaining discrepancies are mainly attributable to lower plume altitudes inferred from UV measurements, in particular in the presence of aerosols, and to the different vertical sensitivities of the two sensors.

Special care was taken to ensure temporal consistency and cross-platform homogeneity among the three IASI instruments, resulting in a long-term record of SO₂ altitude and column measurements well suited for climatological analyses and air quality monitoring applications. We presented the full 18-year IASI time series (2007–2025) of twice-daily atmospheric SO₂ masses and mass-altitude profiles. From this dataset, we also derived a catalogue of volcanic SO₂ plumes with a maximum



mass exceeding 30 kt, reporting for each event the maximum plume mass, the masses below and above 8 km, the altitude
 675 range containing 75% of the total mass, and the mass peak altitude. The IASI time series reveals clear contrasts between
 major tropical and extratropical explosive eruptions. While the bulk of volcanic SO₂ mass is typically confined below or near
 the regional tropopause, mid- and high-latitude Plinian eruptions can inject substantial SO₂ amounts directly into the lower
 stratosphere. The most prominent events detected by IASI include the 2008 Kasatochi, 2009 Sarychev Peak, 2011 Nabro, and
 2019 Raikoke eruptions, for which maximum SO₂ plume masses in the range of 900–1400 kt were retrieved. By contrast,
 680 despite the exceptional altitude reached by its plume, the 2022 Hunga Tonga eruption produced a comparatively moderate SO₂
 atmospheric burden of ~360 kt. Although not explored in this study, the new IASI SO₂ dataset is also suited for long-term
 analysis of anthropogenic SO₂, owing to its temporal consistency and its improved sensitivity in the lower troposphere.

In addition to providing the SO₂ column at the retrieved plume altitude, the algorithm also retrieves SO₂ abundances as-
 suming a set of fixed plume heights between 1 and 60 km. This enables the construction of single-pixel total column averaging
 685 kernels that are suitable for data assimilation in atmospheric models or for deriving more accurate SO₂ column estimates when
 third-party constraints on plume altitude are available. Because of the reduced sensitivity of IASI to the lowermost atmospheric
 layers, a given error in the retrieved plume altitude has a substantially larger impact on the retrieved SO₂ column in the lower
 troposphere than at higher altitudes (Fig. 12). Applying these averaging kernels together with strict external constraints on
 plume altitude makes it possible to reduce this altitude-induced error.

690 Despite the overall robustness of the SO₂ retrieval algorithm, the presence of clouds and volcanic ash remains a significant
 source of uncertainty. Both can attenuate or alter the SO₂ spectral signature, leading to systematic under- or overestimation
 of the SO₂ abundance, depending on the retrieval approach and plume-cloud geometry. While the current algorithm partially
 mitigates these effects, accounting explicitly for clouds and ash within the retrieval framework is an important avenue for future
 development.

695 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 expected availability of the first observations in 2026, the three planned IASI-
 NG sensors 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
 700 consistent IR satellite observations. Moreover, the enhanced instrumental performance of IASI-NG, featuring twice the spectral
 resolution and half the radiometric noise of its predecessor, is expected to significantly improve the SO₂ retrievals, enabling
 enhanced detection capabilities and reduced uncertainties, particularly for weak SO₂ plumes and in the lower troposphere.
 These advances open promising perspectives for future studies of volcanic degassing, anthropogenic SO₂, and their impacts
 on atmospheric composition and climate.



705 6 Data availability

The dataset described in this paper is available from the AERIS data server (<https://iasi.aeris-data.fr>) at <https://dx.doi.org/10.25326/870> (IASI/Metop-A; Clarisse and Franco, 2026a), <https://dx.doi.org/10.25326/869> (IASI/Metop-B; Clarisse and Franco, 2026b), and <https://dx.doi.org/10.25326/868> (IASI/Metop-C; Clarisse and Franco, 2026c).

710 *Author contributions.* LC and BF conceptualized the research, analysed and interpreted the results, prepared the figures, and wrote the first version of the manuscript. LF and NT performed the TROPOMI retrievals. All authors took part in the discussions and revisions of the manuscript.

Competing interests. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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