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article in press

Monitoring Global Volcanic SO₂ Emissions Daily from Space

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Abstract

Monitoring volcanic SO₂ emissions allows investigation of magmatic processes, provides a key tool for monitoring ongoing activity and underpins the quantification of total volcanic degassing budgets. Here, we present daily, global volcanic SO₂ emissions for the year 2020 using satellite SO₂ imagery from the TROPospheric Monitoring Instrument (TROPOMI) and PlumeTraj trajectory analysis, detecting emissions from 20 – 25 volcanoes per day. Our method provides semi-automated quantification of both passive and eruptive degassing as a function of time and altitude. We calculate a total SO₂ emission of 6.1 (± 3.6) Tg, finding that passive, low-altitude (<5 km a.s.l.) emissions dominate eruptive degassing, though highlighting that passive emissions are systematically underestimated due to the limited sensitivity of daily SO₂ imagery. Our results could help to investigate the impact of passive degassing on global climate, and the presented methodology can be applied in near real-time to support continuous monitoring of volcanic unrest from space.

Introduction

Quantification of volcanic gas emissions is a powerful tool for monitoring volcanic activity (Oppenheimer, 2010; Sparks et al., 2012) and understanding magmatic processes (Aiuppa et al., 2010; Burton et al., 2007). Time series of gas emissions collected during eruptions can help forecast eruption evolution (Acocella et al., 2024; Aiuppa et al., 2007; Esse et al., 2025b; Swanson et al., 1985) and reveal magma dynamics (Asensio-Ramos et al., 2025; Burton et al., 2023; Christopher et al., 2010).

35 Volcanic gas emissions (and resulting aerosol species) are also key drivers in both short- and long-term changes to
global climate (Marshall et al., 2022; Robock, 2000). Total volcanic gas emission inventories are typically built by
scaling the SO₂ emissions to measured in-plume gas ratios, for example using a Multi-component Gas Analyser
Systems (MultiGAS) (Aiuppa et al., 2005; Chiarugi et al., 2018; Riddell et al., 2025; Shinohara, 2005) or Open-
Path Fourier Transform Spectroscopy (OP-FTIR) (Burton et al., 2000; Martin et al., 2010; Oppenheimer et al.,
40 1998). SO₂ is the primary target species as, although it is typically the third most abundant volcanic gas after H₂O
and CO₂, it has a negligible background atmospheric concentration and has absorption features at ultraviolet and
infrared wavelengths, meaning it can be quantified remotely from ground, air and satellite platforms (Kern, 2025;
Oppenheimer, 2010; Symonds et al., 1994). Passive SO₂ degassing into the troposphere and subsequent oxidation
to sulfate aerosols may lead to acid precipitation (Charlson and Rodhe, 1982; Oppenheimer et al., 2011) and can
45 promote local ozone depletion when halogens are co-emitted (Roberts, 2018). These continuous emissions,
particularly those aloft in the free troposphere, are thought to significantly influence the atmospheric radiation
budget via cloud condensation and modification of cloud microphysical properties (Graf et al., 1997; Schmidt et
al., 2012), as well as promoting ice crystal growth near the tropopause and thereby modifying water transport into
the stratosphere (Notholt et al., 2005). Recently, the importance of smaller but more numerous volcanic emissions
50 in global climate projections has been recognised (Chim et al., 2023), which is highlighted further by the possibility
of an increase in global radiative forcing due to a reduction in SO₂ emissions from shipping (Yuan et al., 2024).

It is imperative, therefore, that we accurately constrain all volcanic SO₂ emissions, including both smaller passive
degassing and those from major eruptions, to better determine the resulting climate impact, monitor volcanic unrest
55 and examine magma dynamics. From the ground, networks of scanning UV spectrometers have been deployed on
many volcanoes globally to achieve this (Galle et al., 2010; Salerno et al., 2009). These networks automatically
measure passive SO₂ degassing at high time-resolution (every ~10 minutes), however they are usually poorly suited
for quantification of eruptive emissions, where the plume is often optically thick due to high concentrations of gas,
ash and liquid aerosols (Boichu et al., 2015; Hayer et al., 2016; Kern, 2025). Conversely, satellite measurements
60 provide a global overview of volcanic SO₂ emissions, allowing measurements of remote or hard to access locations
that would be difficult or impractical to monitor from the ground (Carn et al., 2016, 2017). However, orbiting
instruments are less suited to quantifying passive emissions in the lower troposphere, and extracting emission rates
from the raw satellite SO₂ imagery is non-trivial (Theys et al., 2013).

65 The launch of the TROPospheric Monitoring Instrument (TROPOMI) in 2017 drastically improved the detection
ability for SO₂ emissions in the troposphere (Theys et al., 2019). To date, the most complete global compilation of
volcanic (and anthropogenic) SO₂ emissions using TROPOMI (as well as the Ozone Monitoring Instrument (OMI)
and the Ozone Mapping and Profiler Suite (OMPS)) is provided by Fioletov et al. (2023), obtained by stacking a
year of cloud-filtered SO₂ images and fitting a plume model to the mean result for each source. This method
70 optimises for sensitivity to tropospheric SO₂ emissions, at the cost of temporal resolution (limiting the monitoring
potential) and with no determination of the plume altitude (a key source of uncertainty in quantifying the SO₂ mass)
or quantification of eruptive emissions. Several automated methods have been developed to identify passive and
eruptive volcanic plumes and quantify the SO₂ mass (e.g. Corradino et al., 2024; Dozzo et al., 2025), while others,
such as the “disk” method (Grandin et al., 2024) or “traverse” method (Merucci et al., 2011), quantify an emission
75 rate from a source, but do not correct for the plume altitude explicitly. Several online portals and databases have
been developed to monitor volcanic SO₂ plumes, including the NASA Global SO₂ monitoring system
(www.so2.gsfc.nasa.gov), the Mounts project (Valade et al. 2019), VolcPlume (Boichu et al., 2025; Boichu &
Mathurin, 2022), the Support to Aviation Control Service (SACS) system (www.sacs.aeronomie.be) and NASA’s
long term, multi-satellite volcanic SO₂ database (Carn 2025).

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In this study, we analyse global daily SO₂ imagery from TROPOMI with the trajectory analysis toolkit PlumeTraj
to calculate daily, altitude-resolved SO₂ emissions from volcanoes globally throughout the year 2020 (chosen as a
test case for its mix of explosive and effusive eruptive styles), with the aim of capturing both passive degassing
and eruptive emissions with a single methodology. PlumeTraj has previously been applied to a range of volcanic
85 activity, including passive degassing (Queißer et al., 2019), effusive eruptions (Esse et al., 2023; Esse et al., 2025a,
b; Hayer et al., 2023) and explosive activity (Burton et al., 2021; Esse et al., 2024; Pardini et al., 2017, 2018). This
makes it the ideal tool to monitor volcanic SO₂ emissions across a range of degassing styles, scales and locations,
complementing existing datasets by providing altitude-corrected SO₂ emission rates for both passive and eruptive
degassing at high (daily) time resolution. One downside to using daily imagery, however, is the relatively limited
90 sensitivity of TROPOMI to SO₂ lower in the atmosphere, especially under cloudy or humid conditions. For this
reason, the calculated SO₂ emissions from passive degassing are assumed to be underestimated, and very weak
sources may not be detected at all.

We suggest that these results will be useful to better incorporate volcanic emissions in future climate modelling by
95 improving constraints on the tropospheric volcanogenic sulfur inventory (Lamotte et al., 2021; Oppenheimer et al.,

2011) with high temporal resolution. The methodology presented utilises freely available data and can be applied in near real-time, opening the potential for semi-automated SO₂ emission monitoring for volcano observatories globally to mitigate the risks of future volcanic activity. This is currently available in a limited fashion for a selection of volcanoes through our near real-time web portal
100 (<https://dailyetna.eps.manchester.ac.uk/dailydata/index.html>), and we aim to expand this in the future.

Data and Methods

TROPOMI

TROPOMI was launched onboard the European Space Agency's Sentinel-5P satellite in October 2017, with data
105 available from May 2018 (Veefkind et al., 2012). Sentinel-5P is a low-Earth near-polar orbiting platform with a local equatorial crossing time of 13:30 (ascending node). TROPOMI acquires 14 – 15 orbits per day, each with a swath width of roughly 2600 km, providing near-global coverage daily (>95% coverage between -7° to 7° latitude and full coverage at higher latitudes). It is comprised of multiple hyperspectral sensors covering UV/Visible (270 – 500 nm), near infrared (675 – 775 nm) and shortwave infrared (2305 – 2385 nm) wavelengths, allowing
110 quantification of several trace gases of interest for air quality, including SO₂ (Theys et al., 2017). The main benefit of TROPOMI is its relatively high spatial resolution of 3.5 x 5.5 km at nadir, resulting in a high enough sensitivity to detect passive volcanic degassing in the troposphere (Theys et al., 2019). This has been further enhanced by the development of a Covariance-Based Retrieval Algorithm (COBRA), offering further improved sensitivity and noise levels than the original operational Differential Optical Absorption Spectroscopy (DOAS) product (Theys et
115 al., 2021). COBRA replaced the DOAS algorithm as the operational product in November 2024, and all historical data have now been re-processed with COBRA.

UV/Visible radiance spectra measured by TROPOMI are analysed to retrieve the Slant Column Density (SCD) of SO₂ in the atmosphere, which is then converted to a Vertical Column Density (VCD) by dividing by a calculated
120 Air Mass Factor (AMF):

$$VCD = \frac{SCD}{AMF} \quad (1)$$

SO₂ column densities are typically reported in Dobson Units (D.U., 1 D.U. = 2.69×10^{16} molecules cm⁻²). The
125 AMF depends on multiple factors, including the viewing geometry, surface albedo, presence of clouds and SO₂
profile shape. As the SO₂ profile is usually not known at the time of measurement, the TROPOMI outputs have
four different SO₂ VCD products: one assuming a well-mixed boundary layer (not typically used for volcanic
applications) and three 1 km thick box profiles centred at 0.5 km above ground level, as well as 7 km and 15 km
above sea level (an additional 3 km profile has been included in operational products since December 2025
130 (Romahn et al., 2025), but is not available for the data used in this study). Due to the strong variability of
TROPOMI's sensitivity to SO₂ with altitude, the plume height is a key source of uncertainty if not constrained and
corrected for (Theys et al., 2019). Therefore, users typically either choose the most representative product for the
scene in question or interpolate between the products to a given plume altitude (e.g. Grandin et al., 2024; Theys et
al., 2013). The source for the plume altitude can be from external information (such as activity reports) or from
135 additional analysis. Some methods have been developed to determine SO₂ layer height spectroscopically for
TROPOMI data, however these require significant columns of SO₂ (>20 D.U. for Hedelt et al. (2019), >5 D.U. for
Theys et al. (2022), >2 D.U. for Fabris et al., (2026)) and so are not applicable to passive degassing. TROPOMI is
not the only instrument capable of detecting volcanic degassing, however it currently has the highest sensitivity to
volcanic SO₂, especially in the lower troposphere, and so we limited our analysis to this single instrument to provide
140 a self-consistent dataset.

Plume Detection and Source Allocation

The volcanic source of each SO₂ pixel in the TROPOMI image is not immediately known at the time of
measurement, and previous applications of PlumeTraj have focused on discrete eruptions where the source of SO₂
can be assumed. However, scaling this up to global data requires additional processing to first cluster nearby SO₂-
145 rich pixels into plumes and then assign those plumes to a source. We follow the methodology presented by Markus
et al. (2023), with the specific analysis steps as follows:

SO₂ rich pixels are first identified using a set of thresholding criteria:

1. The 15 km VCD value must be greater than 0.2 D.U. with a noise level (calculated as the sum of reported
150 random and systematic error) of less than 80% of the VCD;
2. At least 40% of pixels within a 15 km neighbour radius of this pixel must also pass the VCD threshold;
3. The solar zenith angle of the pixel must be less than 65°.

These thresholding parameters were based on the operational SO₂ flag in the TROPOMI L2 product files, though with a lower VCD threshold (0.2 D.U. instead of 0.35 D.U.), a higher allowed noise level (80% instead of 60%) and a more stringent solar zenith angle requirement (65° instead of 75°). These were manually tuned to provide good detection of weak and strong SO₂ plumes, while limiting false positives due to noisy data, especially at high latitude or local winter conditions.

Once the SO₂ pixels are found, they are clustered using a multi-class Density-Based Spatial Clustering of Applications with Noise (DBSCAN) classification scheme, specifically the implementation within the Python Scikit-learn library (Pedregosa et al., 2011). DBSCAN takes a set of points in space and groups nearby points based on the distance between them. It requires two input parameters: *eps*, which sets the maximum distance between two points for one to be in the neighbourhood of the other, and *min_samples*, which assigns the number of additional points in a neighbourhood of a given point for that point to be considered a core point, from which the clusters are built. We used an *eps* value of 15 km and a *min_samples* value of 3.

The resulting clusters must then each be assigned to a source. We first calculate the distances from the edge of each cluster to all source locations in our volcano database, consisting of 114 volcanoes, including 103 from the inventory collated by Fioletov et al. (2023) (not including Mariveles as there are no observed historical volcanic emissions (though anthropogenic emissions are present from the region), La Palma as it erupted in 2021 and Erebus as it is at too high a latitude for our applied thresholding) and 11 additional sources that were identified during manual checks (Balbi (Papa New Guinea), Semeru (Indonesia), Taal (Philippines), Kuchinoerabujima (Japan), Bezymianny (Russia), Semisopochnoi (United States), Okmok (United States), Bogoslof (United States), Pacaya (Guatemala), Poas (Costa Rica) and Fernandina (Ecuador)). Two volcanoes were also switched with nearby sources in the database of Fioletov et al.: Nyiragongo (DR Congo, from Nyamuragira) and Cleveland (United States, from Tana). Utilising a pre-selected database of potential sources could bias results by excluding newly active volcanoes, and so would require manual updating to ensure the source list is accurate. All vent locations and altitudes were taken from the Global Volcanism Program (GVP) database (Global Volcanism Program, 2025). If a cluster is within a defined seed region (a 30 km radius) of a source, then that cluster is assigned to that source. If two or more sources have the cluster within their seed region, then the cluster is assigned to the source with the highest 15 km VCD value within its seed region. If the cluster edge is outside all source seed regions, but a single source is within the bounding hull (i.e. the plume is over the source, but the plume edges are more than 30 km away from the vent location) then the cluster is assigned to that source. If none of the above is true, then the cluster is marked as

unassigned. Anthropogenic emissions are not explicitly excluded from our analysis, however these would need to be co-located with volcanic sources to be mis-assigned. During manual checks (see below), no clear anthropogenic plumes were detected close to any volcanic sources in our database.

All unassigned clusters are then checked for proximity to assigned clusters to allow for elongated plumes made of multiple clusters. Starting at the cluster that is closest to a source, the distance between that cluster and any already assigned cluster is calculated. If the unassigned cluster is within 50 km of an assigned cluster, then the unassigned cluster is assigned to the same source, taking the closest assigned cluster's source in the case of multiple assigned clusters within 50 km. An overview of these steps is given in Supplementary Figure S1.

This method of plume detection and source allocation requires strong enough degassing to produce a detectable plume in the TROPOMI imagery. This means that for weaker sources, low altitude volcanoes or under cloudy conditions the emissions will be either underestimated as the plume disperses below the detection limit downwind or entirely undetected. Therefore, the results should be treated as a lower limit, especially for low altitude sources or for those in typically cloudy or humid environments.

PlumeTraj trajectory-based analysis

With SO₂ pixels clustered and assigned to the corresponding sources, the next step is to calculate the SO₂ emissions. Here, we apply PlumeTraj, a Python-based trajectory analysis toolkit which calculates the plume altitude at the time of measurement as well as the time and altitude that the SO₂ within that pixel was injected into the atmosphere, providing all necessary information to reconstruct the emissions (Burton et al., 2021; Esse et al., 2024; Hayer et al., 2023; Queißer et al., 2019). Here, we utilise the forward implementation of PlumeTraj, as outlined in detail in Esse et al. (2025a, b), with an overview below of the main principles.

PlumeTraj initialises atmospheric trajectories from above the vent location at a range of altitudes (0.2 – 20 km in 0.2 km steps) and at a range of times (every 30 minutes for the 30 hours preceding the time the satellite overpasses the plume), calculating them to an age of 30 hours. All trajectories are generated using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) atmospheric transport model (Stein et al., 2015), driven by the Global Forecast System (GFS) global weather data (0.25° resolution) from the National Oceanic and Atmospheric Administration (NOAA). The location of each trajectory at the overpass time is found and used to define a continuous latitude-longitude grid of irregular four-sided polygons, with the vertices of each defined by the

trajectory locations from trajectories with neighbouring release times and altitudes. Any polygon intersecting a pixel containing SO₂ is marked as a potential solution for that pixel, meaning that the gas contained within the pixel could have been emitted into the atmosphere between the bounding release times and altitudes of the four defining trajectories (see Figure 2 of Esse et al., 2025a). This also provides the plume altitude at the time of measurement by the satellite from the altitude of the trajectories at the overpass time. If multiple adjacent polygons intersect the pixel, then the SO₂ mass is shared across them proportionally to the intersectional area.

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It is usual for multiple solutions to be found for a single pixel due to the four-dimensional nature of the wind fields – trajectories can loop around and return to the same location, and multiple trajectories injected at different altitudes and times can arrive at the same pixel at the time of measurement, depending on wind shear. In such cases, additional information must be used to pick the optimal solution, for example knowledge of the likely injection altitude (such as the vent height for passive degassing or from eruption reports for explosive eruptions) or injection time (from observed timings of discrete eruptions) can be used. For the automated analysis presented here we used the vent height as the target, taking the solution with the closest injection altitude. For reanalysis of eruption plumes, we varied the target values used based on the event, as detailed in the results.

230 Once the plume altitude, injection altitude and injection time are inferred, the time- and altitude-resolved emissions can be reconstructed. Firstly, the SO₂ VCD for each pixel is height-corrected by linearly interpolating between the 0-1 km, 7 km and 15 km AMF values to the calculated plume altitude, which is then converted to an SO₂ mass by multiplying by the pixel area. For plume altitudes above 15 km, the 15 km AMF is used to avoid extrapolation errors (Theys et al., 2017). The contributions from each pixel are then summed on the grid of release time and altitude to construct the total emission history. All uncertainties on the retrieved SO₂ SCD, AMFs and plume height from the trajectory analysis are propagated to the height-corrected VCD and final SO₂ emission.

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Separation of Passive and Eruptive Emissions

To investigate the SO₂ emissions for each individual source, we separate the results into passive and eruptive emissions. Defining what constitutes an eruptive emission may be complex: some volcanoes show sustained unrest or eruption for long periods of time while others have discrete, short-lived events. We identify eruptions through a combination of activity reports collated from the GVP (Smithsonian Institution, <https://volcano.si.edu/>), from significant deviations from the background emission time series and using the NASA Multi-Satellite Volcanic Sulfur Dioxide L4 Long-Term Global Database (MSVOLSO2L4, Carn 2025). This method is imperfect and groups

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many smaller but long-lasting eruptions into the “passive” data but serves to isolate the major deviations in SO₂ emission from the more continuous background activity. All eruptions are re-analysed using manually defined target injection settings as these usually deviated significantly from the default assumption of the vent altitude. The eruptions identified here are given in Table 1, along with the updated target injection settings used for each event.

For most eruptions, the default thresholding is applied to find SO₂ rich pixels, however the eruptions of Shishaldin and Bezymianny occurred during winter and autumn at high latitude, meaning that the standard thresholding is too strict to detect these plumes. Therefore, these eruptions are analysed with more relaxed thresholding, including a lower VCD limit (0.1 D.U.), higher noise threshold (90%), lower neighbour threshold (30%) and no solar zenith angle limit.

Calculation of Daily SO₂ Emissions

The imagery from TROPOMI is split across 14 – 15 orbits each day, each covering a swath over the Earth’s surface. Due to its polar orbit, there is significant overlap in these orbits at high latitude, meaning that there are multiple measurements for the SO₂ column at these locations. To avoid double counting emissions, we mask any pixels overlapping with neighbouring orbits if that pixel is further from the swath centre than the corresponding pixel in the neighbouring orbit, such that each location on the globe is assigned a single SO₂ column value. All unmasked pixels with an age of less than 24 hours are then used to calculate the daily SO₂ emission.

For many weakly emitting sources, the visible plume represents less than 24 hours of emissions due to plume dispersal and dilution below the instrument detection limit and, depending on photochemical conditions, chemical processing of the SO₂ to sulphate aerosol (Voigt et al., 2014). To address this, we calculate a daily mean emission for each source by taking the mean of all time windows in which the emission rate is equal to or higher than 5 kg s⁻¹, taken as a rough general detection limit. If all emissions for a given day are less than 5 kg s⁻¹, then the daily emission rate is set to the maximum value for that day to avoid setting these emissions to zero. An example for emissions from Langila volcano (Papua New Guinea) on 12 September 2020 are shown in Figure 1, demonstrating the drop off in reconstructed emissions as a function of plume age.

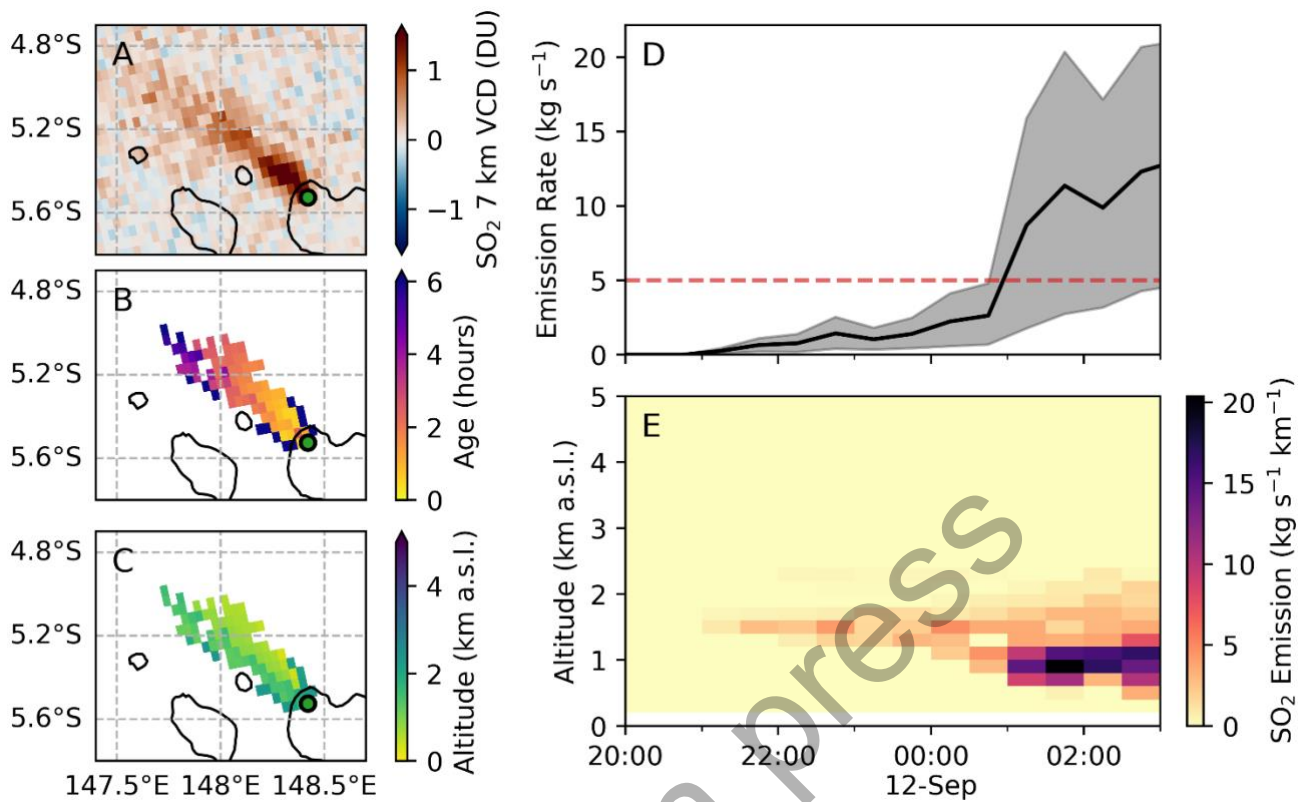


Figure 1: Example PlumeTraj results for Langila volcano (Papa New Guinea) on 12 September 2020, showing: [A] the 7 km SO₂ VCD data; [B] the retrieved plume ages; [C] the retrieved plume altitudes; [D] the reconstructed SO₂ emission rate (with the 5 kg s⁻¹ threshold given by the red dashed line) and [E] the reconstructed SO₂ emission intensity. The source location is given by the green circles. Times are in UTC.

The true detection limit will be highly variable, depending on meteorological cloud conditions (including meteorological cloud cover and height), vent location, the vent/emission altitude, season, and viewing geometry, therefore choosing a single value will not be suitable for all sources. Determining a daily detection limit for each source would improve the accuracy of this approach and will be the subject of future work. The mean emission for eruptions was calculated across all time windows as explosive activity is often not continuous for the full 24 hours and the SO₂ emission is typically stronger for eruptive degassing than for passive degassing, and so is less susceptible to dropping below the instrument detection limit.

Calculation of Yearly Emissions

We also calculate the mean yearly SO₂ emission rate for each volcano. This is achieved by masking the daily emission rate time series for days on which meteorological clouds are likely obscuring the plume or when

285 observations are not possible (due to low light levels during local winter at high latitude sources, or for missing satellite orbits). Daily emissions are masked if any of the following criteria are true:

1. The mean cloud fraction within a 30 km radius is above 0.5, the mean cloud height is equal to or higher than the vent altitude and the mean emission rate is below 5 kg s^{-1} ;
2. There are no successful SO_2 retrievals for pixels within 30 km of the vent (due to low light levels or
290 missing data);
3. The minimum solar zenith angle within 30 km of the vent is greater than 70° .

For this we use the cloud fraction and height products provided as part of the Level 2 TROPOMI SO_2 output files (Loyola et al., 2018). The mean yearly emission rate is then taken as the mean of all unmasked days. For high latitude volcanoes, this means that the local winter emissions were be assumed to have the same mean emission
295 rate as those throughout the summer, potentially giving either over- or underestimation if there was significant emission variation between the seasons.

Results and Discussion

Plume Detection and Allocation

300 The automatic plume detection and source allocation typically finds ~ 20 plumes from volcanic sources per day, with slightly more in the northern hemisphere summer (Supplementary Figure S2). Figure 2 gives an example of the source allocation results for the Kamchatka region on 22/04/2020 (orbit number 13076). On this day multiple sources were emitting SO_2 simultaneously with a range of emission strengths, dispersal directions and plume sizes. The applied source allocation algorithm works well generally, however the plume from Avachinsky merged into
305 that from Karymsky and is grouped into a single plume allocated to Karymsky, while the proximity of Bezymianny and Klyuchevskoy ($\sim 10 \text{ km}$) means that accurately distinguishing the correct source is very difficult. This highlights some of the difficulties of this approach.

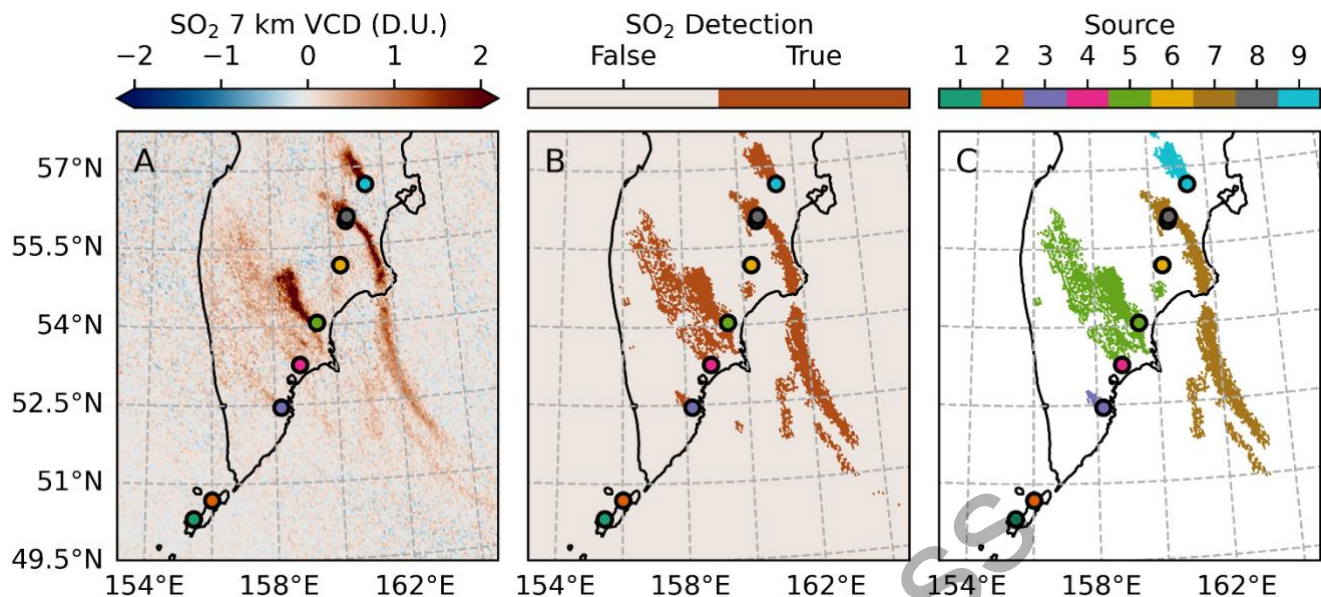


Figure 2: Example of source allocation results for the Kamchatka region on 22/04/2020. [A] 7 km SO₂ VCD product. [B] SO₂ detection mask. [C] Allocated sources. Source locations are given by the coloured circles. Sources included in the scene (south to north) are: (1) Chikurachki, (2) Ebeko, (3) Mutnovsky, (4) Avachinsky, (5) Karymsky, (6) Kizimen, (7) Bezymianny, (8) Klyuchevskoy and (9) Sheveluch.

The SO₂ image for each volcano on each day is checked manually and marked whether a plume can be seen by eye. This is then compared to the automated source allocation results to assess the performance. The results of this are given in Figure 3, split by source region and marked as one of: true positive (both the manual check and the automated analysis assign a plume to that source), true negative (neither the manual check nor the automated analysis assign a plume to that source), false positive (the automated analysis assigns a plume to the source but the manual check does not) or false negative (the automated analysis does not assign a plume to the source and the manual check does).

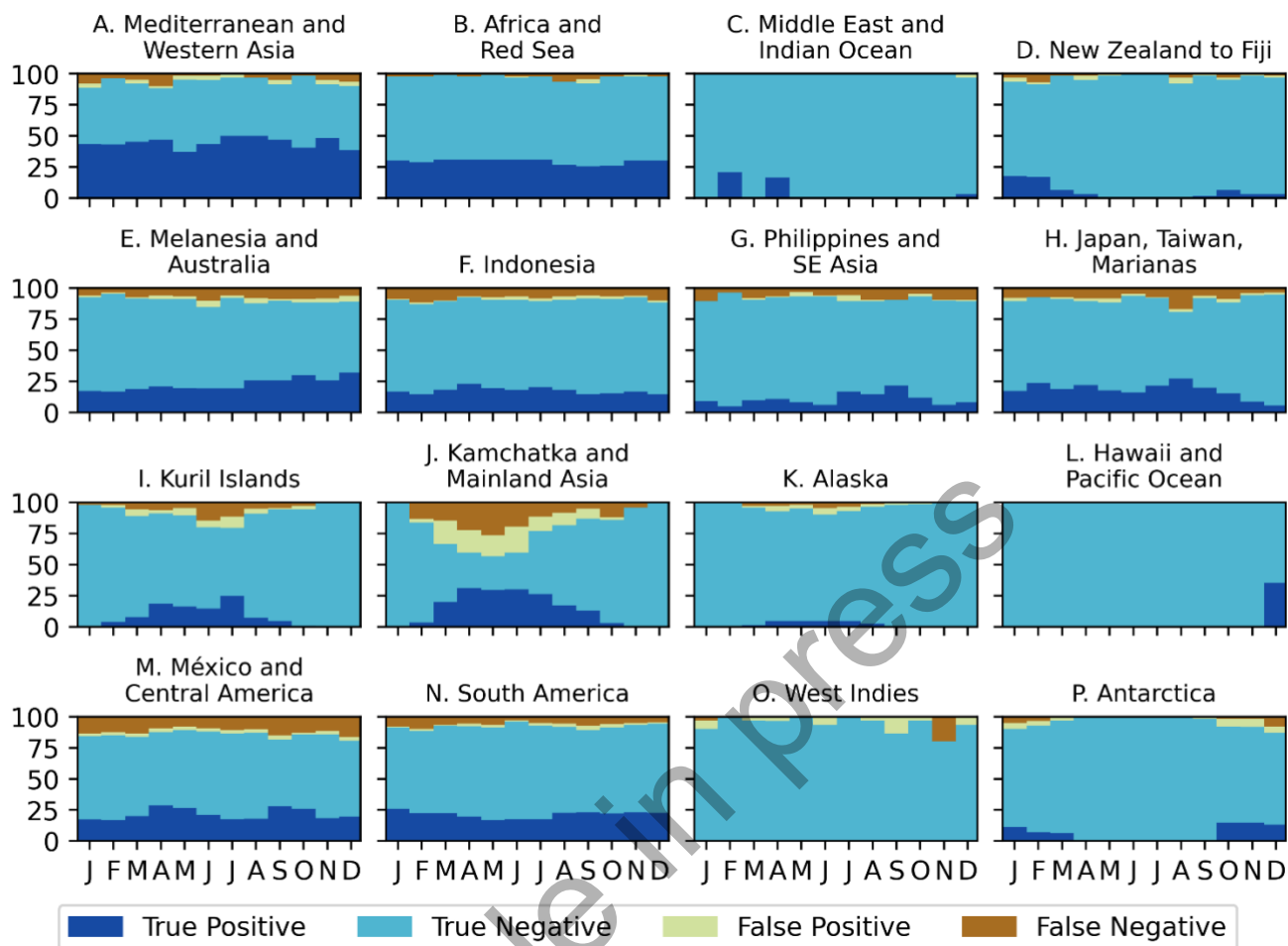


Figure 3: Source allocation performance by region (as defined by the GVP).

These results show that generally the automated source allocation identifies plumes in agreement with the manual check, typically in over 90% of cases. Performance is lower for regions with many persistently active volcanoes (e.g. Indonesia, Kamchatka and Mainland Asia, México and Central America) where many plumes are on the edge of detection and/or the sources are in close proximity. It is worth noting that this analysis assumes that the manual check is the truth, however in reality it is often difficult to definitively know which is the correct source when they are physically close. For example, many of the false negative and false positive values for Kamchatka and Mainland Asia are from plumes being assigned to one of Bezymianny and Klyuchevskoy, which, as already noted, are only ~10 km apart. This makes assigning a clear source impossible, even manually.

SO₂ Emissions

Global Overview

An overview of the total (passive and eruptive) detected SO₂ emissions for each volcano is given in Figure 4, showing both the source locations and ranked emissions, coloured by the number of days with detected plumes. This shows that the majority of the detected SO₂ emitted in 2020 is dominated by continuously degassing sources. Of the top 10 sources, 9 are characterised by continuous passive degassing with detections almost every day of the year. The total detected SO₂ across all sources is 6.1 (± 3.6) Tg. The largest single emitter is Nishinoshima, which produced 1.0 (± 0.5) Tg SO₂ (16% of the total), while the top ten volcanoes emitted a total of 3.9 (± 2.2) Tg (64% of the total). For context, the 1991 eruption of Pinatubo in the Philippines emitted roughly 15 – 19 Tg SO₂ (Guo et al., 2004), and the 1783/4 eruption of Laki in Iceland emitted roughly 122 Tg SO₂ (Thordarson and Self, 2003).

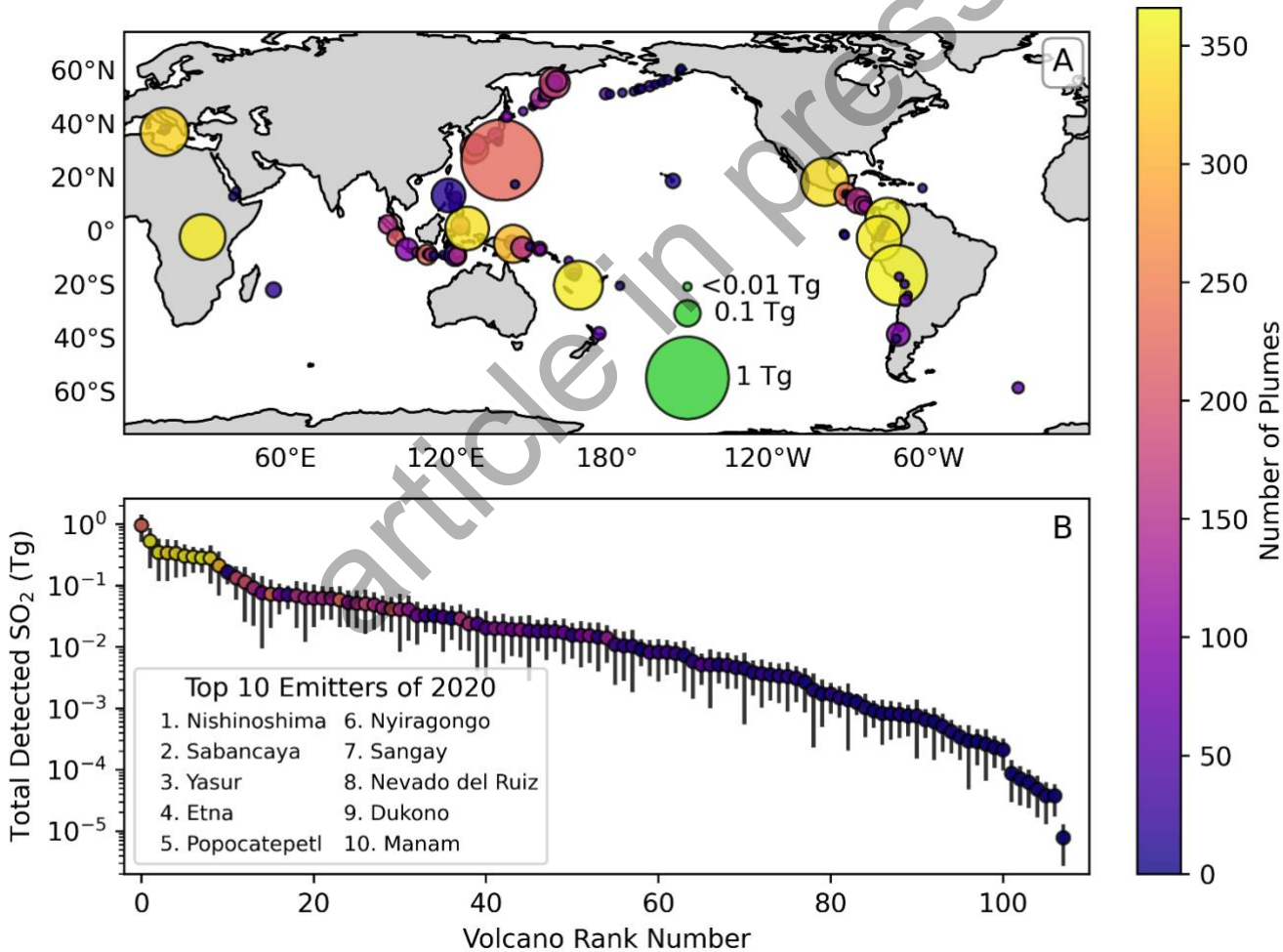


Figure 4: Overview of total SO₂ emissions of all sources. [A] Map of source locations, with markers sized by total SO₂ emitted (see green circles for scale). [B] Total SO₂ emission from all sources ranked by total SO₂ emission. All points are coloured by the number of plumes found for each source. Note 7 sources included in the database had no detected emissions.

Although the largest SO₂-emitting volcanoes dominate, the roughly exponentially decaying distribution suggests a long tail of weaker emitters that are likely underestimated or undetected due to satellite sensitivity limits when using daily imagery. To assess the overall performance of the PlumeTraj analysis we compare the mean yearly passive emissions to those calculated by Fioletov et al. (2023), which takes the observed TROPOMI SO₂ columns around each source every day, rotates the data around the source so that the wind direction is aligned and stacks the resulting data for a year (removing cloudy data or high SO₂ column pixels to avoid eruptive emissions). A plume model is then fitted to the resulting stacked emissions to determine the mean emission rate for that volcano. This provides much greater signal to noise than is available in the daily measurements, as well as mitigating the impact of clouds by masking cloudy pixels from the analysis, at the expense of both altitude and time information. Fioletov et al. (2023) increase the SO₂ emissions calculated with TROPOMI by 22% to align with previous and ongoing measurements using OMI and OMPS, so here we reduce their reported emissions to their original value to provide a consistent comparison with our results. The results of the two methods are shown in Figure 5.

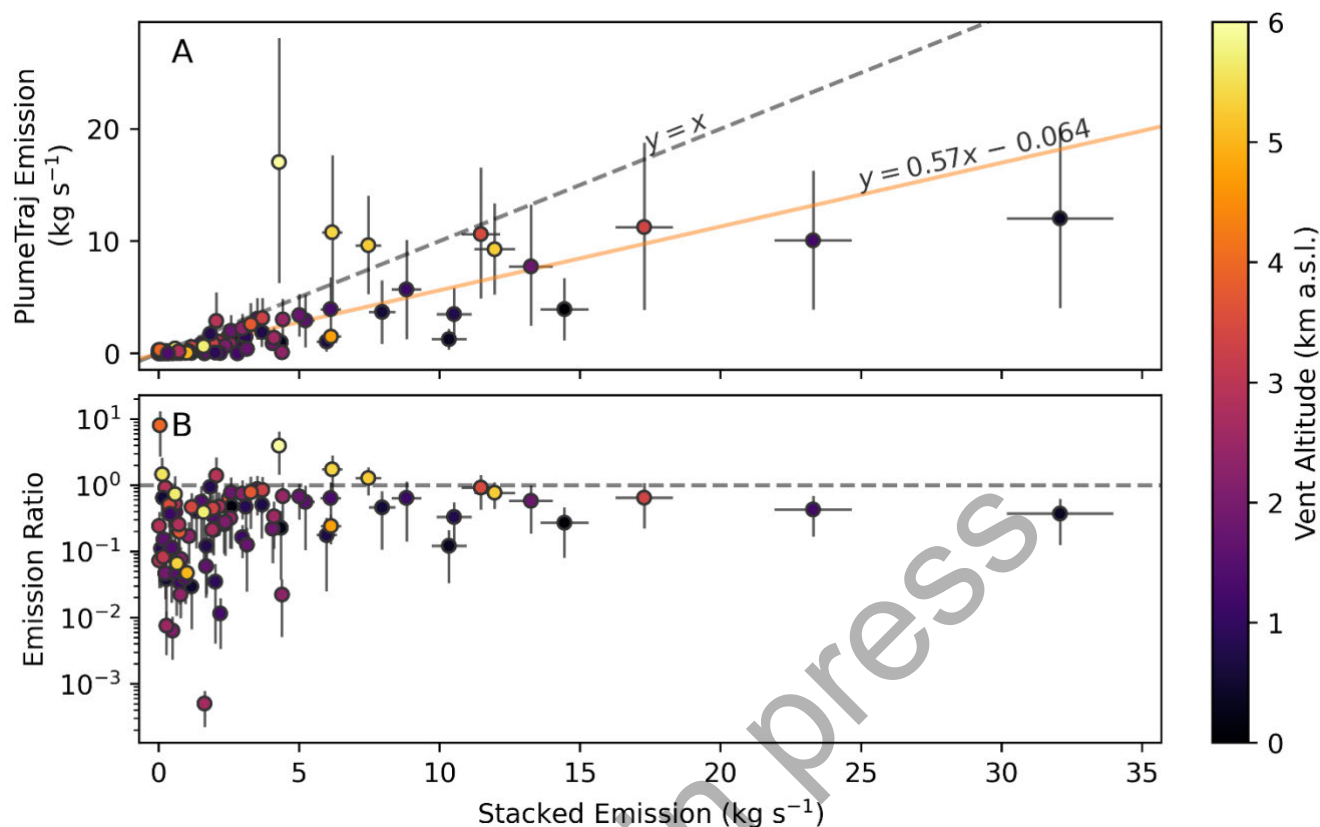


Figure 5: Comparison between the yearly mean PlumeTraj and stacked emission rates calculated by Fioletov et al. (2023). [A] gives the direct comparison, with the identity line and fitted orthogonal distance regression shown. [B] Emission ratio of the two methods (PlumeTraj / Stacked). All points are coloured by the vent altitude.

These results show a general linear relationship between the two methods, with a fitted orthogonal distance regression giving a slope of $0.57 (\pm 0.05)$. A spread can be seen based on vent altitude, with PlumeTraj calculating relatively lower emissions for lower altitude volcanoes compared to the stacked emissions. A larger difference can be seen for the weaker emitters, with PlumeTraj calculating significantly lower emission rates for volcanoes under 5 kg s^{-1} . The total SO₂ emission from the stacked method is $12.4 (\pm 0.8) \text{ Tg}$, just over double the total calculated by PlumeTraj.

We expect that our results are systematically underestimated due to the limited sensitivity of the daily TROPOMI imagery compared to averaging a year of data. Many weaker sources will be entirely below the detection limit of the applied thresholding, while dispersal of emissions downwind of the vent will lead to an apparent loss of SO₂, which is not accounted for in our results. This is likely also the cause of the altitude dependency in the comparison with PlumeTraj emissions to those reported by Fioletov et al. (2023), as volcanoes emitting SO₂ lower in the

atmosphere will be harder to detect due to both the reduced sensitivity of TROPOMI to SO₂ closer to the surface, as well as an increased likelihood of being obscured by meteorological cloud. However, it is worth highlighting that a systematic impact of the use of a fixed AMF value for each volcano analysed by Fioletov et al. (2023) may also contribute to this discrepancy. These results highlight again the importance of the long tail of weaker, but more ubiquitous degassing volcanoes that may be underestimated or entirely undetected using daily measurements alone.

To assess the accuracy of the eruptive emissions calculated with PlumeTraj we compare our results to the NASA MSVOLSO2L4 dataset (Carn 2025), a long-term dataset which combines satellite remote sensing with independent observations of plume height to calculate the atmospheric mass loadings for all significant eruptions visible to satellites (Figure 6). As this dataset quantifies SO₂ mass loading, not the emission rate, we only compare short-lived explosive eruptions to avoid double counting SO₂ emissions for more prolonged activity.

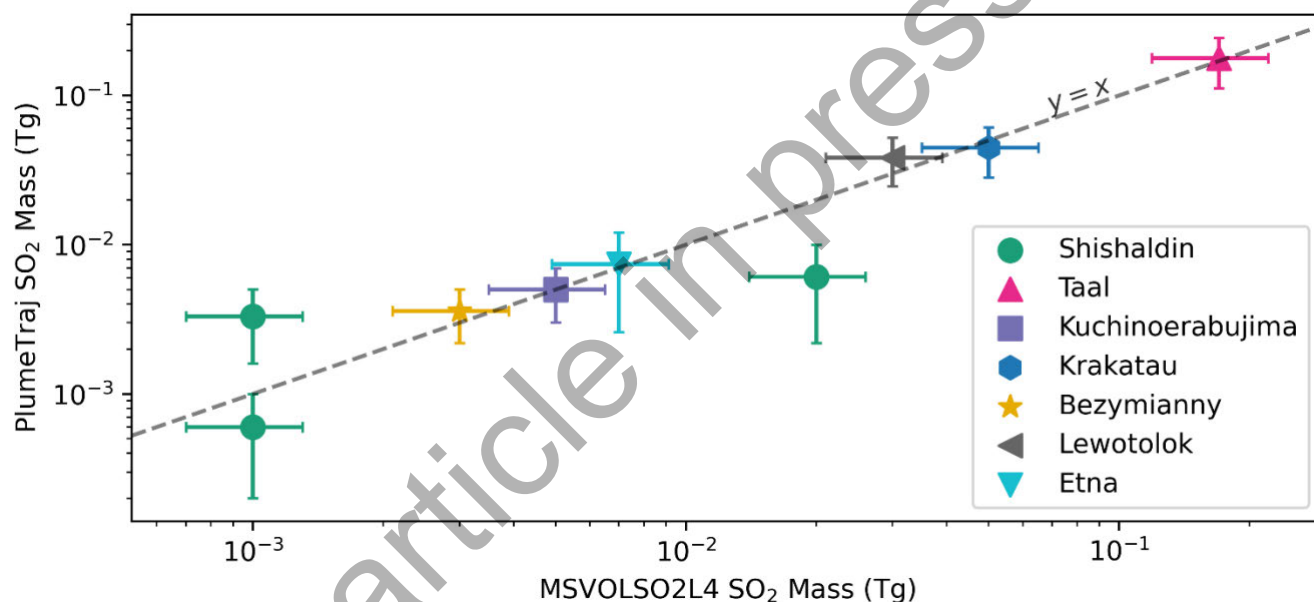


Figure 6: Comparison of explosive SO₂ mass loadings calculated by PlumeTraj and the MSVOLSO2L4 dataset, with uncertainty in PlumeTraj results given by the vertical bars. Error bars for the MSVOLSO2L4 data are set to 30%.

The retrieved masses from PlumeTraj are almost all within uncertainty of the MSVOLSO2L4 dataset except for the Shishaldin eruptions, which we ascribe to the fact that these eruptions took place at high latitude (54.8°N) and during winter, and so are close to the noise limit.

Emissions by Region

We categorise volcanic emissions in 2020 by source region as defined by the Global Volcanism Program (2025) (Figure 7). These results show that volcanic emissions are spread across the world but are dominated by volcanoes around the Pacific Ocean. The strongest passively emitting region is South America, due to the high vent altitudes and, therefore, easier detection of emissions. The Japan, Taiwan and Marianas region has the highest overall emission, dominated by the eruption of Nishinoshima.

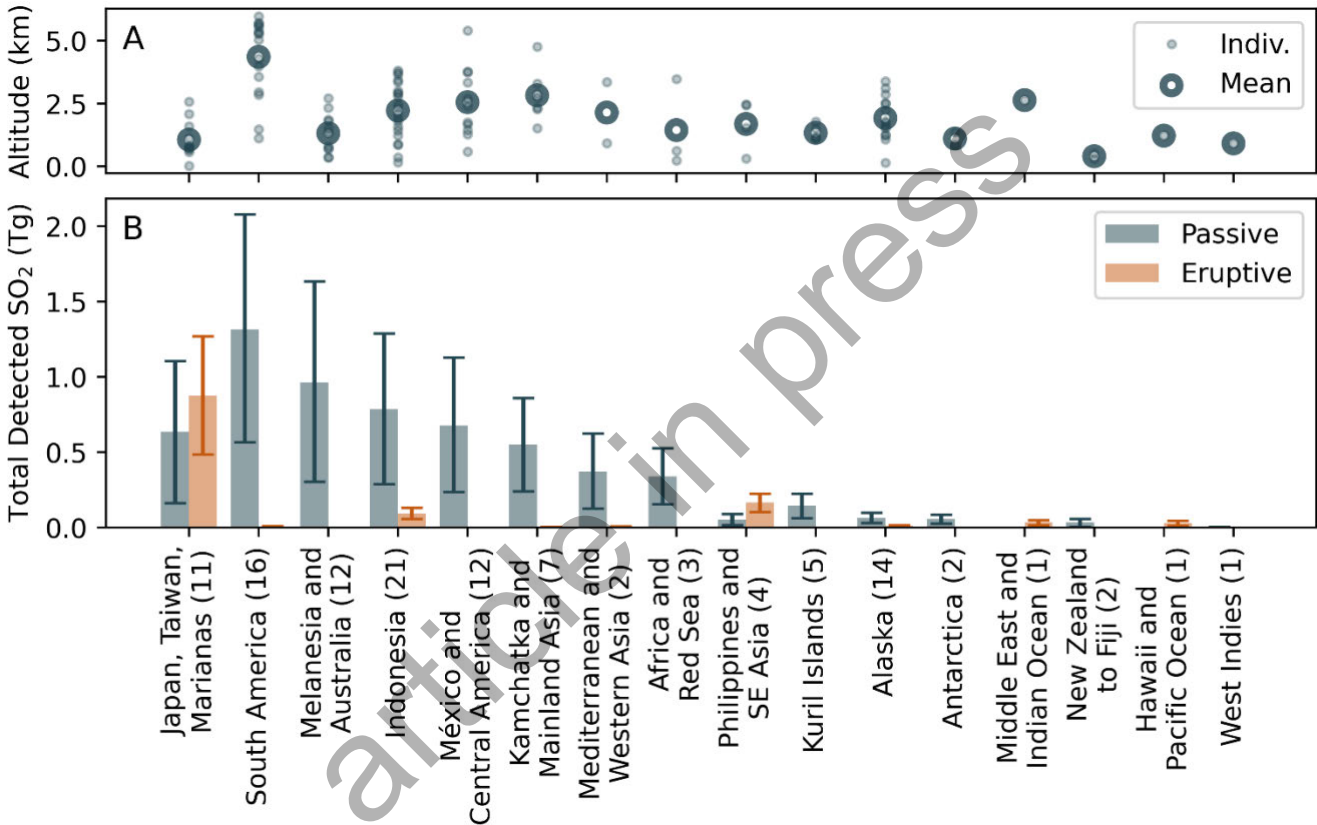


Figure 7: Breakdown of detected SO₂ emissions by region (as defined by the GVP). [A] Vent altitudes, with individual values given by smaller points and the mean for each region given by the larger point. [B] Total SO₂ emissions for each region, split between passive (blue) and eruptive (orange) emissions. The numbers in brackets denote the number of sources in each region.

We can also inspect the relative magnitude of SO₂ emitted from each region throughout the year (Figure 8, taking the weekly mean for clarity). Here we display the SO₂ emission from each region as a fraction of the total calculated global emission. This again highlights that the eruption of Nishinoshima dominated the global SO₂ emissions

throughout the summer but also shows the time evolution of degassing on a regional scale. For example, emissions from Kamchatka can be seen to be stronger in the first half of the year (note they are not visible during northern hemisphere winter), reducing significantly after the summer. These emissions are not dominated by a single source, suggesting some regional control on the activity across the arc.

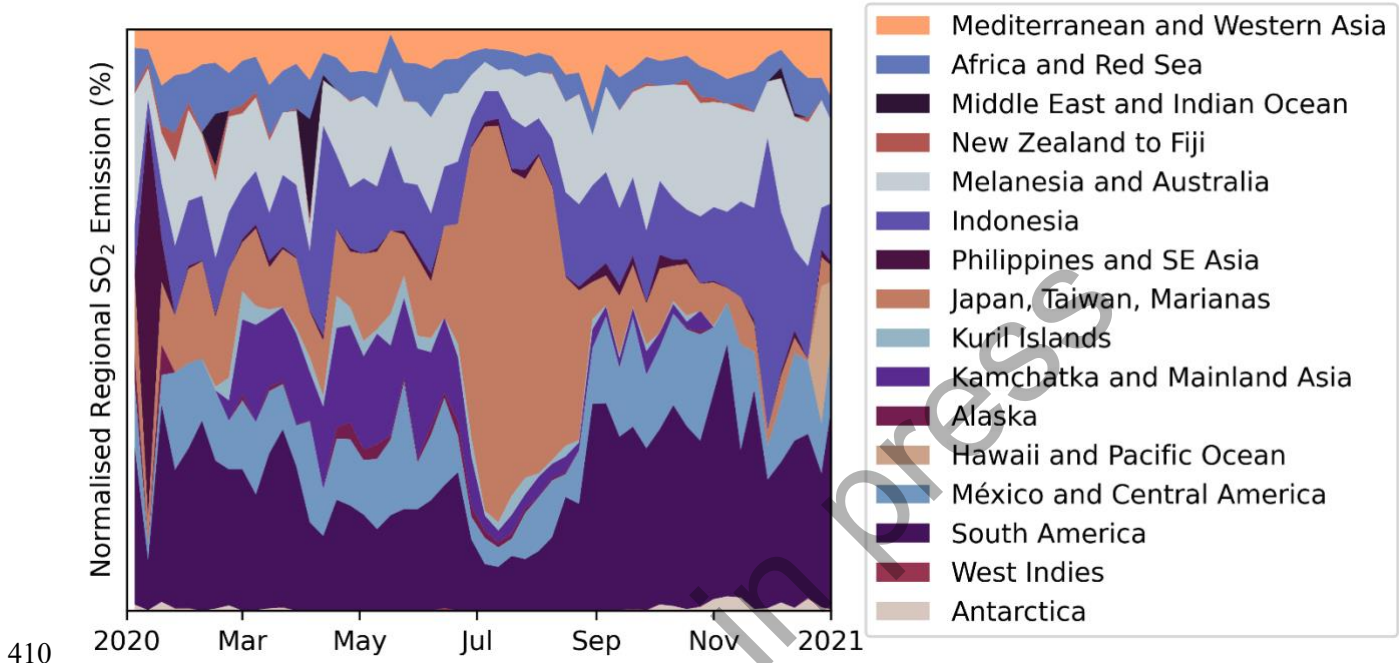


Figure 8: Temporal evolution of the weekly SO₂ emission (passive and eruptive) by region as a fraction of the total global SO₂ emission. Note the ordering of the legend reflects the ordering of regions in the figure (top to bottom).

Integrated Emissions

We extract the detected passive emissions for each volcano, summing across all sources to calculate an integrated daily SO₂ emission product for the globe as a function of both absolute altitude above sea level and height above the vent (Figure 9). Although the height-dependant sensitivity of TROPOMI to SO₂, particularly in the troposphere, will impact the absolute SO₂ emissions calculated, we find that the emission strength follows roughly the same distribution as vent altitudes. This suggests that the altitude of the passive emissions is primarily controlled by vent altitude, with emissions generally returning at or just above vent altitude. This is perhaps not surprising given that this is the target altitude used in our analysis, however we highlight there must be a valid solution at this altitude to be assigned to it. Interestingly, there is a void in volcanoes with a vent altitude in the range of 4.5 – 5 km, leading to a drop in the overall emissions at this altitude. This is primarily due to most volcanoes being within the 0 – 4 km altitude range, with a separate population (mostly in South America) at roughly 5 km. Some speckle of emissions

can also be seen at very high altitudes; these are largely due to errors in the analysis either from inaccuracies in the
 425 wind fields or from incorrect source allocation, but the overall contribution from these errors is small compared to
 the signal at vent altitude.

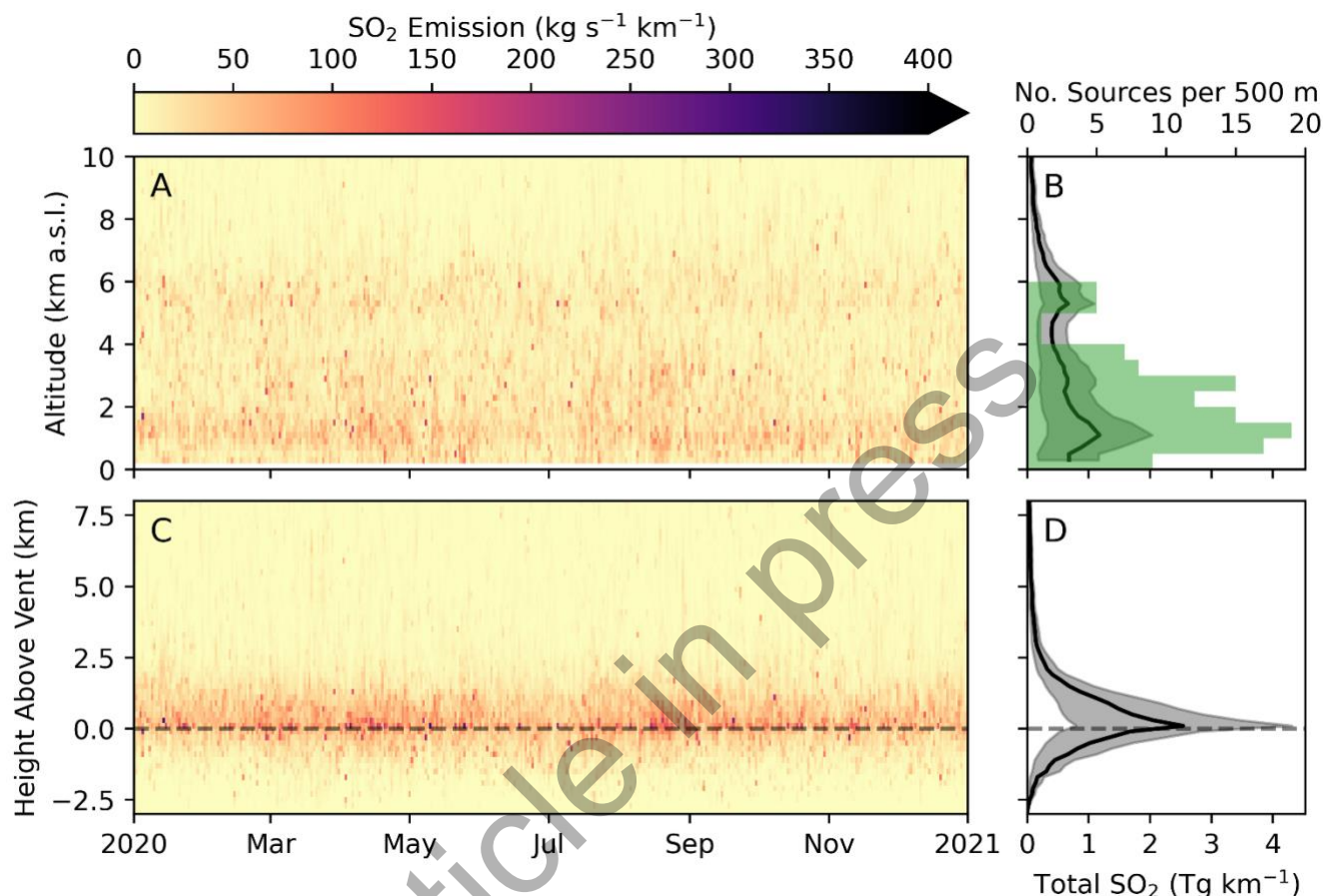
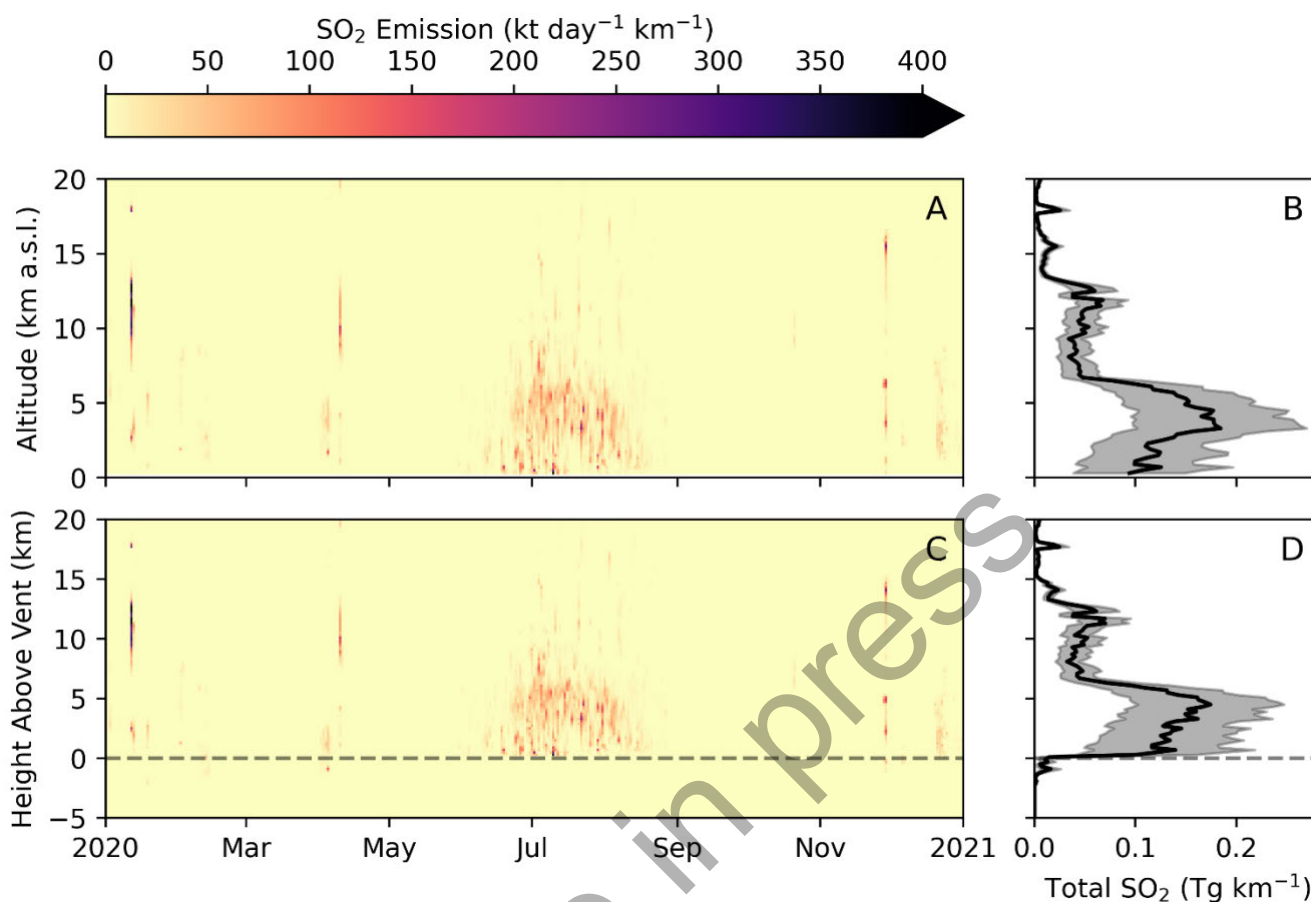


Figure 9: Detected global daily passive SO_2 emissions for all sources. [A] Passive SO_2 emissions with time and absolute altitude above sea level. [B] Total SO_2 emitted as a function of absolute altitude above sea level (black line), with a histogram of vent altitudes of the volcanoes used in this study (green bars). [C] Passive SO_2 emissions normalised to above vent height. [D] Total SO_2 emitted as a function of height above the vent. Shaded regions give calculated uncertainty.

We apply the same analysis to the detected eruptive emissions, again calculating a global daily emission as a function of altitude and height above vent (Figure 10). These results show a wider range of injection altitudes as
 435 expected (in particular for explosive events), with the emission time-series dominated by the sustained eruption of Nishinoshima during the summer months. Most of the emissions are injected above the vent height, with the exception of the April eruption of Piton de la Fournaise which was a flank eruption roughly 700 m below the vent altitude (Global Volcanism Program, 2020).



440 **Figure 10: Detected global daily eruptive SO₂ emissions for all sources. [A] Eruptive SO₂ emissions with time and absolute altitude above sea level. [B] Total SO₂ emitted as a function of absolute altitude above sea level. [C] Eruptive SO₂ emissions normalised to above vent height. [D] Total SO₂ emitted as a function of height above the vent. Shaded regions give calculated uncertainty.**

A comparison of the detected daily emission rates for both passive and eruptive emissions is shown in Figure 11.

445 The passive emissions are steady at an average of $150 (\pm 100) \text{ kg s}^{-1}$, showing little significant variation across the year. Several eruptions (Taal, Krakatau, Nishinoshima and Lewotolok) have a daily emission rate that is higher than the passive background, however, except for Nishinoshima, these were short-lived events. The total passive SO₂ emission is $4.9 (\pm 3.0) \text{ Tg}$, compared to $1.2 (\pm 0.5) \text{ Tg}$ for the eruptive emissions, highlighting again that the calculated passive emissions are systematically underestimated due to the detection limit of daily TROPOMI

450 imagery.

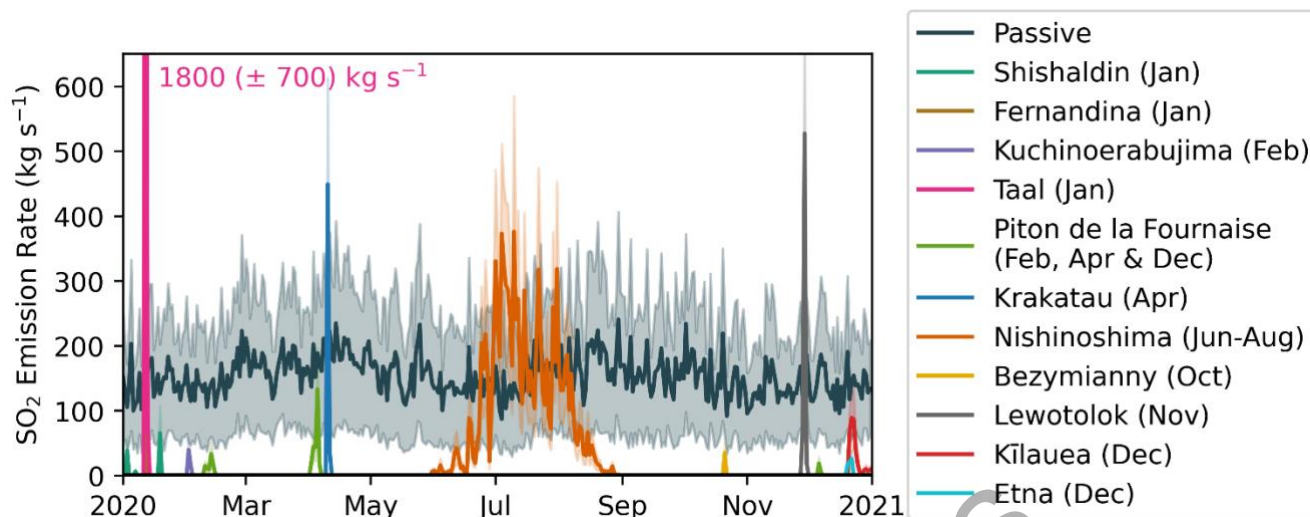


Figure 11: Comparison of passive (blue) and eruptive (multi-coloured) SO₂ emission rates throughout 2020. Note the y-scale has been clipped for clarity, with the eruption of Taal reaching a maximum of 1800 (± 500) kg s⁻¹. Shaded regions give calculated uncertainty.

455 **Monitoring Potential: Nishinoshima Eruption**

One key benefit of the PlumeTraj approach is the high temporal-resolution of the SO₂ emission data. We highlight that this is more useful than methods that quantify the mass loading in the atmosphere each day (or at higher time resolution) as these can lead to double counting of SO₂ if the gas persists for more than 24 hours. This is particularly important for monitoring applications, where day-to-day variations in measured SO₂ emissions, alongside other
 460 monitoring data, can be used to inform eruption response. Here, we investigate the eruption of Nishinoshima in more detail as an example of the monitoring potential of this method.

The eruption of Nishinoshima was characterised by three phases (Kaneko et al., 2022). Phase 1 (4 December 2019 – 19 June 2020) was characterised by effusive lava flows with Strombolian activity, which increased the size of
 465 the island and built up the pyroclastic cone. Phase 2 began on 20 June when activity switched to be more explosive, with intensive lava fountaining and significantly higher effusion rates (peaking at ~30 m³ s⁻¹ compared to the average ~5 m³ s⁻¹ in Phase 1). Activity diminished towards the end of Phase 2, transitioning to Phase 3 on 27 July, which was characterised by primarily phreatomagmatic activity and little-to-no growth of the pyroclastic cone. The end of the eruption was set to 20 August when no more significant ash emissions were detected. Gas emissions
 470 from the eruption of Nishinoshima led to degradation of air quality in Jeju, South Korea (Park et al., 2025), and Imizu City, Japan (Watanabe et al., 2021).

An overview of the combined (passive and eruptive) SO₂ emissions from Nishinoshima is given in Figure 12. In Phase 1 there is a constant emission of ~5 kg s⁻¹ at low altitude (<2 km a.s.l.) which increases dramatically in Phase 2 to ~300 kg s⁻¹ at the start of July (an increase of nearly 2 orders of magnitude). These emissions are still relatively low altitude, with the bulk of emissions being injected below 7 km. From July onwards the emission rates decay steadily into Phase 3. After the reported end of the eruption (20 August) there are still detectable SO₂ emissions of ~5 kg s⁻¹ until 20 September.

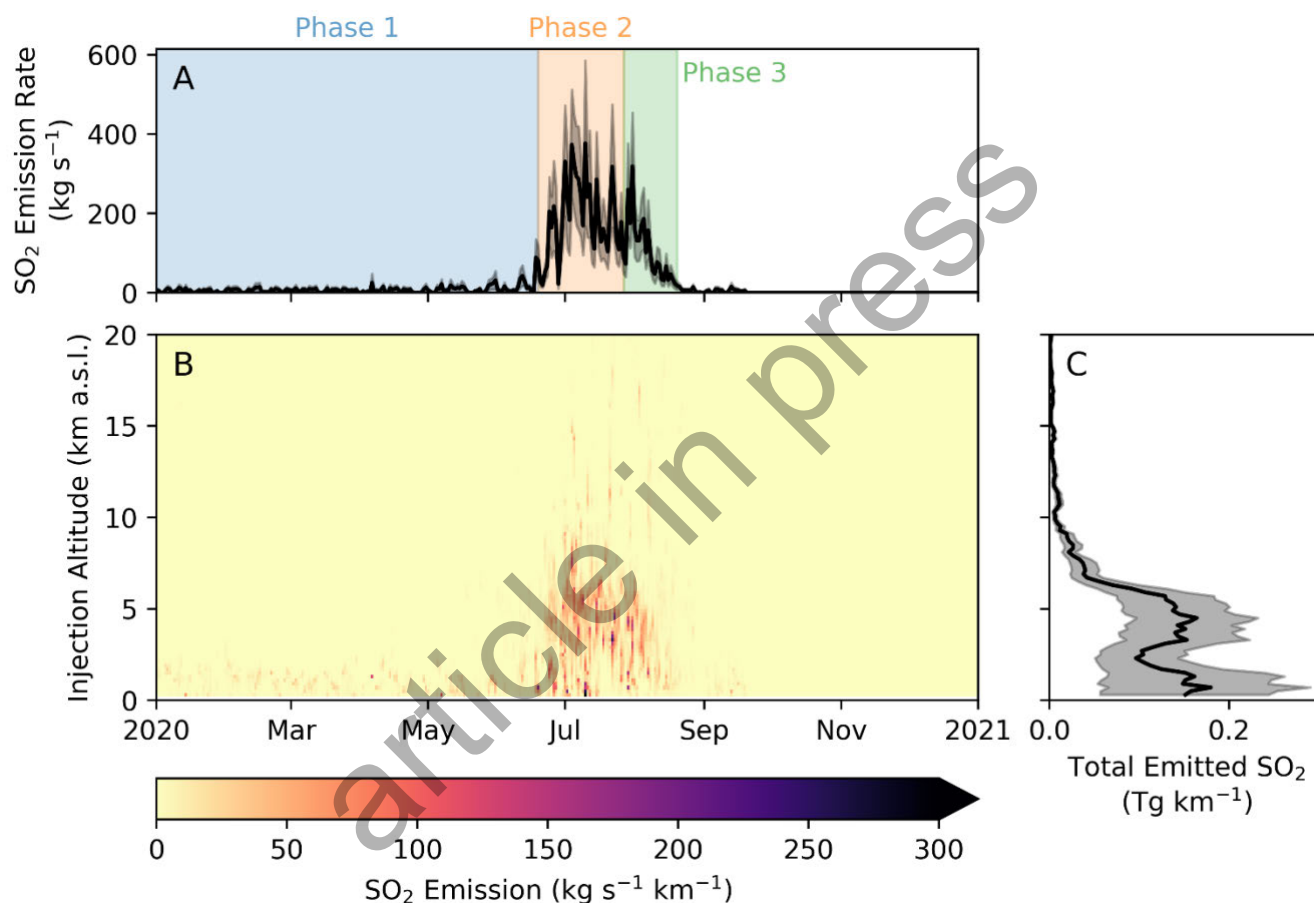


Figure 12: Overview of the total SO₂ emissions from Nishinoshima. [A] Daily SO₂ emission rate. [B] SO₂ emission intensity as a function of time and altitude. [C] Total emitted SO₂ mass as a function of altitude. Shaded regions give calculated uncertainty.

The transition from effusive to explosive activity is reflected in the daily SO₂ emissions calculated with PlumeTraj in terms of both the emission rate and altitude. This supports the reported SO₂ plumes and overall interpretation of Kaneko et al. (2022), who suggest that the activity in Phase 1 was driven by the extrusion of already degassed

magma being pushed out by the ascent of a fresher batch of volatile-rich magma. The transition to Phase 2 occurred when this fresh magma reached the surface, presenting more vigorous activity in the form of higher explosivity and lava fountaining. The decay in the measured SO₂ emissions could then reflect the draining of the supply of fresh magma as the eruption progressed until the eruption could no longer support itself. As well as providing
490 insights into the magmatic processes driving the eruption, the time- and height-resolved SO₂ emissions could also be used to drive plume dispersal simulations to forecast and mitigate risks from degradation of air quality.

Limitations and future work

Here we provide a brief overview of the main limitations of the presented methodology, as well as planned future work.

495 *Accuracy of PlumeTraj analysis*

PlumeTraj relies on several assumptions to calculate SO₂ emission rates, including accurate meteorological data, correct source allocation and negligible loss of SO₂ (both dropping below the threshold detection limit and through chemical conversion). This could be improved in the future by incorporating multiple satellite sensors in a data fusion approach (providing multiple plume location data to reduce degeneracy in possible trajectory solutions),
500 utilising more precise meteorological data or ensemble meteorology to better constrain errors arising from the wind information (Harvey et al., 2020), and incorporating chemical loss processes (e.g. Oppenheimer et al., 1998) to better reconstruct the source emissions.

Plume detection and source allocation

The current implementation of plume detection and source allocation achieves >90% accuracy in most regions, dropping to >80% for México and Central America and >70% for Kamchatka and Mainland Asia. The main areas
505 for improvement are for densely clustered sources where plumes are easily mis-allocated or merge into single clusters. A machine-learning approach, for example using a random forest classifier, could potentially improve this, though would require carefully prepared training data. Implementing time- and latitude-dependent pixel thresholding could also improve detection of emissions for high-latitude volcanoes where the noise is significantly
510 higher in local winter.

Sensitivity of daily SO₂ imagery

One major drawback of using daily SO₂ imagery is the finite sensitivity of TROPOMI to SO₂, due to the pixel size and inherent instrumental noise. This means that many weak emitters will be entirely below the detection limit, and passive emissions are likely systematically underestimated due to the dispersal of the plume downwind of the source leading to the apparent loss of SO₂ with plume age, and from being obscured by meteorological cloud. This is particularly the case for low-altitude sources due to the decreasing sensitivity of TROPOMI to SO₂ with decreasing altitude, potentially explaining the altitude-dependant discrepancy between passive emissions calculated with PlumeTraj and those of Fioletov et al. (2023). For this reason, our results present a lower bound on global SO₂ emissions. This issue is not unique to TROPOMI, but an inherent limitation of passive satellite remote sensing of atmospheric trace gases.

Definition of eruptive vs passive degassing

One key source of uncertainty in the separation of passive and eruptive degassing is defining eruptions. We investigated using the GVP eruptions database (Global Volcanism Program, 2025), and, while useful in identifying some eruptions, this was not suitable as a blanket definition as some volcanoes were classed as continuously erupting throughout 2020 (for example Etna is marked as having a Volcanic Explosivity Index 3 eruption from 2013 to 2022). Using a multi-sensor approach, e.g. incorporating satellite thermal and deformation data as well as SO₂, may be able to provide a more robust eruption classification, though this would still require manually defined thresholds.

VCD Height Correction

To calculate the height-corrected VCDs, PlumeTraj linearly interpolates between the three box-profile AMFs available in the operational SO₂ product, introducing systematic errors into the height-corrected VCD. This error is typically <10% for low cloud pixels (<0.5 cloud fraction), with maximum error at 2-3 km and 10-11 km altitude. However, the error can increase to ~80% for some fully cloudy pixels as the shape of the averaging kernel curve becomes highly non-linear (see supplementary figure S3). Fully recalculating the AMF would improve this, however the information stored in the TROPOMI product files is not sufficient (due to data size limitations) and we do not have access to the full look-up table used to calculate the AMF values (Theys et al., 2017). Note that as of December 2025, a 3 km product has been added to the operational TROPOMI SO₂ output (Romahn et al., 2025), which will help to mitigate the impact of this error in the future.

540 We also do not currently make use of the SO₂ layer height product that is now available within the TROPOMI SO₂ products (Hedelt et al., 2019) as the required SO₂ column is very high (>20 D.U.). However, Fabris et al. (2026) have developed an improved SO₂ layer height product with much higher sensitivity (>2 D.U.), and so incorporating this into our workflow could improve our automated analysis in the future, especially for eruptive degassing.

Expansion of time-series and additional sensors

545 In this study we restrict analysis to the year 2020 and only use TROPOMI data. In the future it is planned to extend this analysis to the full TROPOMI time series (May 2018 – present) and produce a near real-time processor to provide continuous monitoring for volcanic activity world-wide. It would also be possible to apply the same methodology to older UV instruments to increase temporal coverage (such as OMI or OMPS), as well as to infrared instruments (such as the Infrared Atmospheric Sounding Interferometer, IASI) to provide better coverage at high-
550 latitude winter and during nighttime observations (though with lower sensitivity to low-altitude emissions). It will also be possible to include additional recent polar orbiting instruments, such as Sentinel-5 (European Space Agency, 2020) and IASI New Generation (IASI-NG), and recent hyperspectral geostationary instruments, such as the Geostationary Environmental Monitoring System (GEMS), Tropospheric Emissions: Monitoring of Pollution (TEMPO) and Sentinel-4. Adopting such a multi-sensor approach would both improve the temporal coverage and
555 provide a self-consistency check on retrieved emissions.

Conclusions

In this paper we calculate daily global volcanic SO₂ emissions as a function of altitude for the year 2020 by combining satellite remote sensing and trajectory analysis. The primary benefit of this approach is the generation
560 of daily, height-resolved emissions from both passive and eruptive with a single, consistent methodology, providing a comprehensive overview of volcanic degassing visible from space. The detected SO₂ emissions are dominated by persistently degassing sources, with 4.9 (± 3.0) Tg of passively emitted SO₂ compared to 1.2 (± 0.5) Tg SO₂ from eruptions. The eruption of Nishinoshima (Japan) is the single largest source at 1.0 (± 0.5) Tg, over double the second largest emitter (Sabancaya, Peru) and accounting for 16% of all detected volcanic SO₂ and 83% of the total
565 eruptive emissions in 2020. The main downside to using daily imagery is that the calculated emissions will be detection-limited due to the reduced sensitivity of TROPOMI to SO₂ lower in the atmosphere and under cloudy or humid conditions, particularly for passive emissions. This means that detected emissions will be underestimated

and weaker emitters may be undetected entirely. Therefore, the calculated passive SO₂ emissions present a lower limit, especially for low altitude volcanoes or those in particularly cloudy or humid regions.

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We demonstrate the ability of our approach to monitor ongoing volcanic activity in near real-time through the example of the eruption of Nishinoshima, where variations in the daily SO₂ emission strength and altitude reflect changes in eruption style and intensity. Applying the same methodology to other sensors, such as infrared instruments (e.g. IASI) or additional Low Earth Orbit and Geostationary satellites (e.g. Sentinel-4, Sentinel-5, GEMS), would further improve the acquisition frequency and temporal coverage of observations, supplementing other existing efforts to monitor volcanic SO₂ emissions from space.

Investigating the SO₂ emissions as a function of altitude reveals that almost all SO₂ was emitted in the lowest 5 km of the troposphere, with passive emissions almost entirely emitted at or just above vent altitude. Only emissions from the eruptions of Taal, Krakatau and Lewotolok reached the upper troposphere or lower stratosphere. This has potential implications for the climate impact of these emissions, as the lifetimes of the emitted gases (and subsequent aerosols) are strongly controlled by the altitude of injection. We suggest that the results presented here could be used in the future to help constrain the impact of smaller magnitude, but more ubiquitous, volcanic degassing in future climate modelling, as well as help provide a better constraint on the impact of volcanic SO₂ emissions on tropospheric chemistry. Our results also highlight the strong link between the distribution of active vent heights and the injection altitude of volcanic gases into the troposphere, suggesting that changes in the altitude of volcanically active arcs through geological time could provide a tectonic influence on the long-term climate influence of volcanic degassing.

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Data Availability

All TROPOMI data is available through the Copernicus Dataspace Ecosystem (<https://dataspace.copernicus.eu/>) and GFS meteorological data is available from NOAA (<https://www.ready.noaa.gov/data/archives/gfs0p25>). All
600 PlumeTraj results presented in this paper are available here: <https://doi.org/10.48420/31267816>.

Author Contribution

B. Esse: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M. Burton:** Writing – review & editing, Project
605 administration, Methodology, Funding acquisition, Conceptualization. **C. Hayer:** Writing – review & editing, Software, Methodology, Conceptualization. **M. Queißer:** Writing – review & editing, Software, Methodology, Conceptualization.

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Tables

Table 1: Identified eruptions with start and end dates of PlumeTraj analysis, as well as applied settings for the target injection altitude and time used. Note that dates refer to when the SO₂ plumes were measured and so may be after the eruption onset date. All altitudes are defined as above sea level.

Volcano Name (and Number)	Start Date	End Date	Target Injection Settings
Shishaldin (311360)	2020-01-03	2020-01-03	Altitude (5 km)
	2020-01-07	2020-01-07	
	2020-01-19	2020-01-19	
Taal (273070)	2020-01-13	2020-01-13	Altitude (12 km)
Fernandina (353010)	2020-01-13	2020-01-13	Altitude (3 km)
Kuchinoerabujima (282050)	2020-02-03	2020-02-03	Altitude (8 km)
Piton de la Fournaise (233020)	2020-02-11	2020-02-15	Altitude (7km, first day only)
	2020-04-02	2020-04-06	Altitude (5 km)
	2020-12-07	2020-12-07	Altitude (5 km)
Krakatau (262000)	2020-04-11	2020-04-11	Altitude (10 km)
			Time (2020-04-10 15:30)
Nishinoshima (284096)	2020-06-01	2020-08-31	Altitude (5 km)
Bezymianny (300250)	2020-10-22	2020-10-22	Altitude (11 km)
Lewotolok (264230)	2020-11-29	2020-11-30	Altitude (5 km)
			Time (2020-11-29 05:00)
Etna (211060)	2020-12-21	2020-12-22	Altitude (7km)
Kīlauea (332010)	2020-12-21	2020-12-31	Altitude (3 km)