



Multi-Satellite and Lagrangian Transport Analysis of Volcanic SO₂ Plume Evolution

S. Prasanth¹, N. Anand², S. K. Satheesh^{1,3,4}, and K. K. Moorthy¹

¹Divecha Centre for Climate Change, Indian Institute of Science, Bengaluru, Karnataka, India

²School of Earth, Environmental and Sustainability Sciences, Indian Institute of Science Education and Research Thiruvananthapuram, Thiruvananthapuram, Kerala, India

³Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bengaluru, Karnataka, India

⁴DST-Centre of Excellence in Climate Change, Indian Institute of Science, Bengaluru, Karnataka, India



APARC
Atmospheric Processes
And their Role in Climate



Lead Presenter: S. Prasanth (prasanthphy57@gmail.com)

1. Abstract

The explosive eruption of Hayli Gubbi volcano on 23 November 2025, after remaining dormant for over 12,000 years, injected a large mass of SO₂ into the upper troposphere.

Using multi-satellite observations, together with Massive-Parallel Trajectory Calculations, we have examined the plume’s transport dynamics. Retrievals from the TROPOspheric Monitoring Instrument indicate that a total of 0.18 ± 0.02 Tg of SO₂ was released.

The initial injection height of SO₂ plume is estimated to be 9-14 km using SEVIRI 10.8 μm brightness temperature.

The plume was then advected over 16,000 km (horizontally) in four days by the prevailing subtropical westerly jet, at the same time remaining confined between 9 and 14 km altitudes with no evidence of stratospheric intrusion.

2. Data and Methodology

Data used in the present study

S.No	Instrument/Reanalysis	Parameters
1.	TROPOMI onboard Sentinel-5 Precursor	SO ₂ vertical column density (DU)
2.	SEVIRI onboard MSG	Brightness temperature at 10.8 μm
3.	ERA5	u and v wind components, vertical velocity (ω), temperature (K), and humidity (%)

SO₂ mass estimation

The mass of SO₂ is then calculated for each valid grid within the black dashed line shown in top left panel in Sect. 4 and summed to obtain the total plume mass as described in Grandin et al. (2024). The conversion relies on the standard relationship between column density and mass loading. For each ith pixel, the SO₂ mass in that pixel is computed as:

$$\text{Mass of } SO_2 = \sum_{i=1}^n VCD_{SO_2(i)} \cdot A_i \frac{k_{DU} \cdot M_{SO_2}}{N_A} \quad (1)$$

$VCD_{SO_2(i)}$ is the vertical columnar density of SO₂ (DU) in the ith grid, A_i is the area of the ith grid (m²), M_{SO_2} is the molar mass of SO₂ (64.06 g mol⁻¹), N_A is the Avogadro number (6.022×10^{23} mol⁻¹), and k_{DU} is the conversion factor from DU to molecular column density (2.6867×10^{20} molecules m⁻² DU⁻¹).

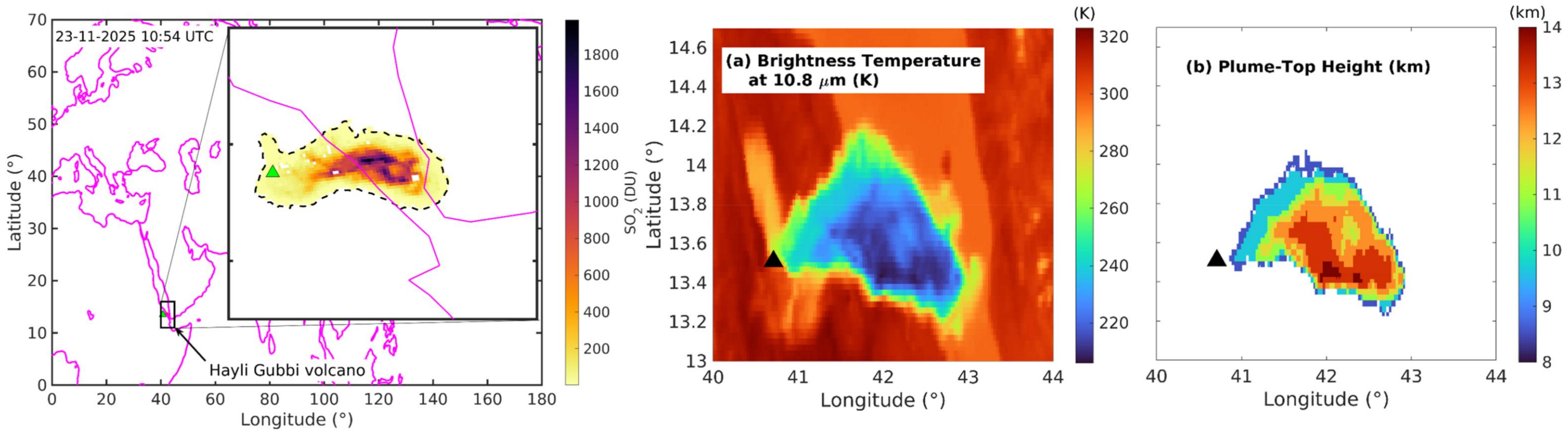
3. Lagrangian Transport Model Setup and Configuration

Meteorological parameters from ERA5 reanalysis are fed into the Massive-Parallel Trajectory Calculations (MPTRAC) model, version 2.2 (Hoffmann et al., 2022).

It was employed to simulate the atmospheric transport and dispersion of air parcels carrying SO₂ following the explosive eruption of the HG volcano.

Category	Parameter	Details
Model Configuration	Model Name	Massive-Parallel Trajectory Calculations (MPTRAC), version 2.2
	Simulation Type	Forward trajectory (atmospheric transport and dispersion of SO2)
	Time Step	10,800 seconds (3 hours)
	Simulation Period	23 November 2025 (09:00 UTC) to 27 November 2025 (21:00 UTC)
	Number of Air Parcels	10,000
	Injection Altitude	9 to 14 km above sea level
	Release Location	Latitude $13.51 \pm 0.1^\circ\text{N}$, Longitude $40.62 \pm 0.1^\circ\text{E}$ (HG volcano)
Data Used	Primary Data Source	ERA5 reanalysis
	Meteorological Input Fields	u and v wind components, vertical velocity (ω), temperature (K), and humidity (%)
	Spatial Resolution	Regrided to $1^\circ \times 1^\circ$ (approx. 111 km $\times$ 111 km at the equator)

4. Total Emission of SO₂ Mass and Its Injection Height



Left panel: A representative plot of total columnar SO₂ (DU) on 23-11-2025 at 10:54 UTC. The filled green triangle in the inset marks the location of the HG volcano. The black dashed line indicates the boundary of the SO₂ plume.

It reveals a prominent, elongated plume of elevated SO₂ extending predominantly eastward from the source volcano over the Red Sea region. Peak SO₂ concentrations in the plume exceed 1800 DU in the core, while values remain below 100 DU across a span of ~360 km zonally and ~180 km meridionally, covering an area of ~24,000 km². The estimated injected SO₂ mass (~2.5 hours after the eruption) was 0.18 ± 0.02 Tg.

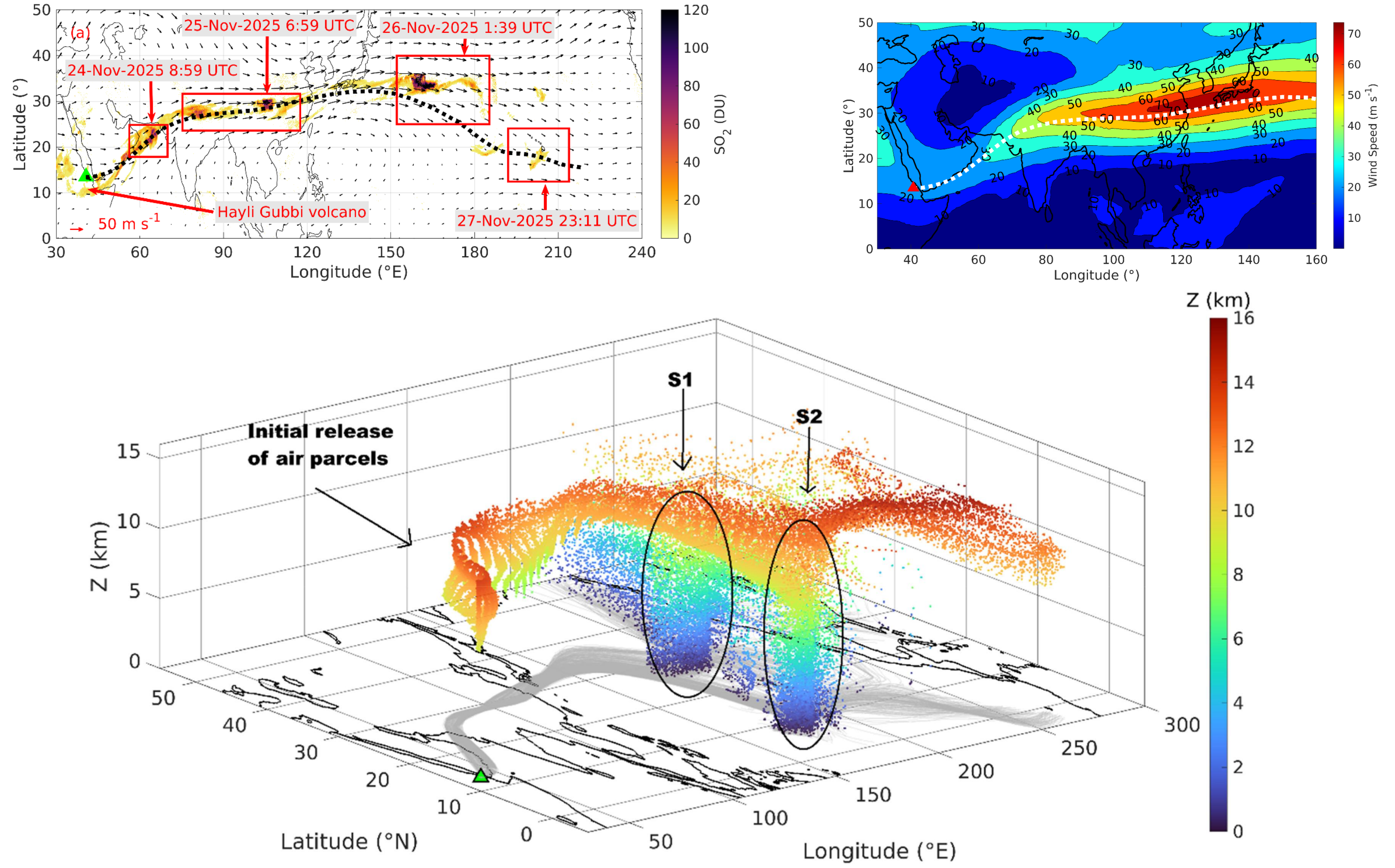
Middle panel: Brightness temperature (BT, K) at 10.8 μm retrieved from the SEVIRI sensor aboard Meteosat Second Generation-2 at 10:57 UTC on 23 November 2025, showing the HG volcanic plume.

The volcanic plume appears as a distinct region below 280 K (dark blue shaded pixels; middle panel) compared to the surrounding region with BT10.8 above 300 K. The coldest BT10.8 of the plume is found to be 206 K, while progressively warmer temperatures occur towards the plume margins. Plume-top height was estimated by matching the BT10.8 with the nearest ERA5 atmospheric temperature profile.

Right panel: Retrieved volcanic plume-top height (km) derived by matching the SEVIRI BT at 10.8 μm with the corresponding ERA5 atmospheric temperature profile. The black triangle marks the location of the HG volcano (13.5°N , 40.7°E).

The retrieved plume-top heights range from approximately 9 to 14 km, with the highest altitudes (14 km) coinciding with the coldest BT10.8 (206 K) in the central-southern part of the plume

5. Transport of SO₂ Plume and Its Interaction with Subtropical Jet



Top left panel shows the transport of volcanic SO₂ plume observed using TROPOMI. **Top right panel** shows the ERA5 wind field at upper troposphere. **Bottom panel** shows 3D dispersion of MPTRAC simulated air parcels initialized at 9–14 km above the HG volcano eruption on 23 November 2025. The air parcels are coloured by altitude, and the corresponding surface projection is shown in grey. The green triangle indicates the HG volcano location.

6. Summary and Conclusion

This study investigated the emission, long-range transport, and impacts of the volcanic SO₂ plume released by the HG eruption on 23 November 2025 using a combination of satellite observations (TROPOMI, and SEVIRI) and Lagrangian trajectory modeling (MPTRAC). The key findings of the investigation are as follows:

- The HG eruption produced very high SO₂ vertical column densities exceeding 1800 DU near the source on 23 November 2025 (estimated ejected mass of about 0.18 Tg). Nevertheless, its SO₂ mass is orders of magnitude are lower than the major volcanic ejections of the last century, such as El Chichon (~3.6 Tg) and Mt. Pinatubo (~20 Tg).
- Following the eruption, the plume was efficiently transported eastward over 16,000 km within four days, reaching the western Pacific, primarily within the upper troposphere (9–14 km altitude), under the influence of the subtropical westerly jet and associated jet streak.
- Forward trajectory simulations using the MPTRAC model confirmed that the SO₂-laden air parcels remained confined between 9 and 14 km altitude with minimal vertical ascent, indicating that the plume did not intrude into the stratosphere and was confined to the troposphere throughout its transport.

These findings highlight the significant influence of upper tropospheric jet streaks on the long-range transport and dispersion of volcanic SO₂ plumes, which can aid the evaluation and refinement of atmospheric transport models.

7. References

Grandin, R., Boichu, M., Mathurin, T., & Pascal, N. (2024). Automatic Estimation of Daily Volcanic Sulfur Dioxide Gas Flux From TROPOMI Satellite Observations: Application to Etna and Piton de la Fournaise. *Journal of Geophysical Research: Solid Earth*, 129(6), e2024JB029309. <https://doi.org/10.1029/2024JB029309>

Hoffmann, L., Baumeister, P. F., Cai, Z., Clemens, J., Griessbach, S., Günther, G., Heng, Y., Liu, M., Mood, K. H., Stein, O., Thomas, N., Vogel, B., Wu, X., & Zou, L. (2022). Massive-Parallel Trajectory Calculations version 2.2. (MPTRAC-2.2): Lagrangian transport simulations on graphics processing units (GPUs). *Geoscientific Model Development*, 15(7), 2731–2762. <https://doi.org/10.5194/GMD-15-2731-2022>