Università degli Studi di Napoli Federico II

Scuola Politecnica e delle Scienze di Base
Dipartimento di Ingegneria Industriale

Laurea Magistrale in Ingegneria Aerospaziale

An Automatic Procedure for Volcanic SO_2 Flux Retrieval using TROPOMI L2 Products

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- Analysis of Scenario
- Problem Statement
- State of the Art
- Developed Algorithm
- Study Cases
- Results & Validation
- Conclusions & Future Developments

SO_2 It is the 3rd most abundant volatile compound and a critical proxy for volcanic activity and ash.

Insights into magmatic processes

Hunga Tonga-Hunga Ha'apai eruption (24/12/2021)

Threats to aviation security

Plane dusted in volcanic ash (Guatemala, 2021)

Effects on local environment

- Promotion of ozone destruction
- Conversion into H_2SO_4 and subsequent deposit as acid rain
- Formation of cloud condensation nuclei

ERUPTIONS UNPREDICTABILITY

Continuous, real-time monitoring is required.

UNMONITORED REMOTE AREAS

Scarce or nonexistent ground-based systems.

Space-based Remote Sensing Techniques

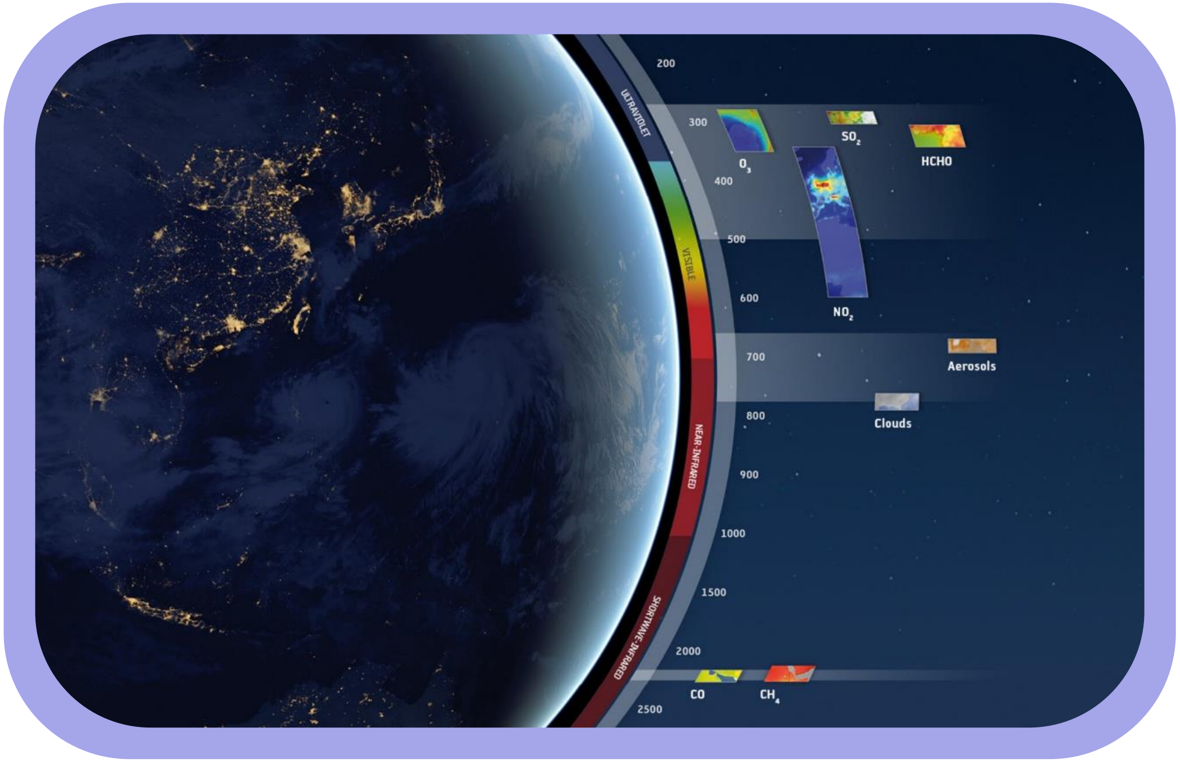
LACK OF AUTOMATIC TOOLS

Need for an automatic and reliable algorithm to quantify SO_2 fluxes in NRT.

Sentinel-5P TROPOMI

1st Copernicus mission dedicated to monitoring the Earth's atmosphere

Nadir-viewing imaging spectrometer with 3.5 km x 5.5 km spatial resolution



CIRCULAR TRAVERSE METHOD

Satellites sensors
do not measure fluxes,
they retrieve **SO_2 Vertical Columns** (VCs)

Several **techniques** exist
to convert SO_2 VCs
into flux estimates
based on **mass conservation**

Traverse Method
using concentric
circular transects

PYTHON PROJECT FLOW

S5P TROPOMI Data
TROPOMI data
download from [29]

File .nc containing the
geophysical products
(L2 products)
downloaded from the Copernicus Browser

Wind Data
Wind Speed data
download from [65]

File .csv containing the
vertical atmospheric sounding profiles
downloaded from the open-source
University of Wyoming website

Projection Parameters

Crater geographic coordinates
Chosen map projection: **UTM** or **EQC**

Developed Algorithm

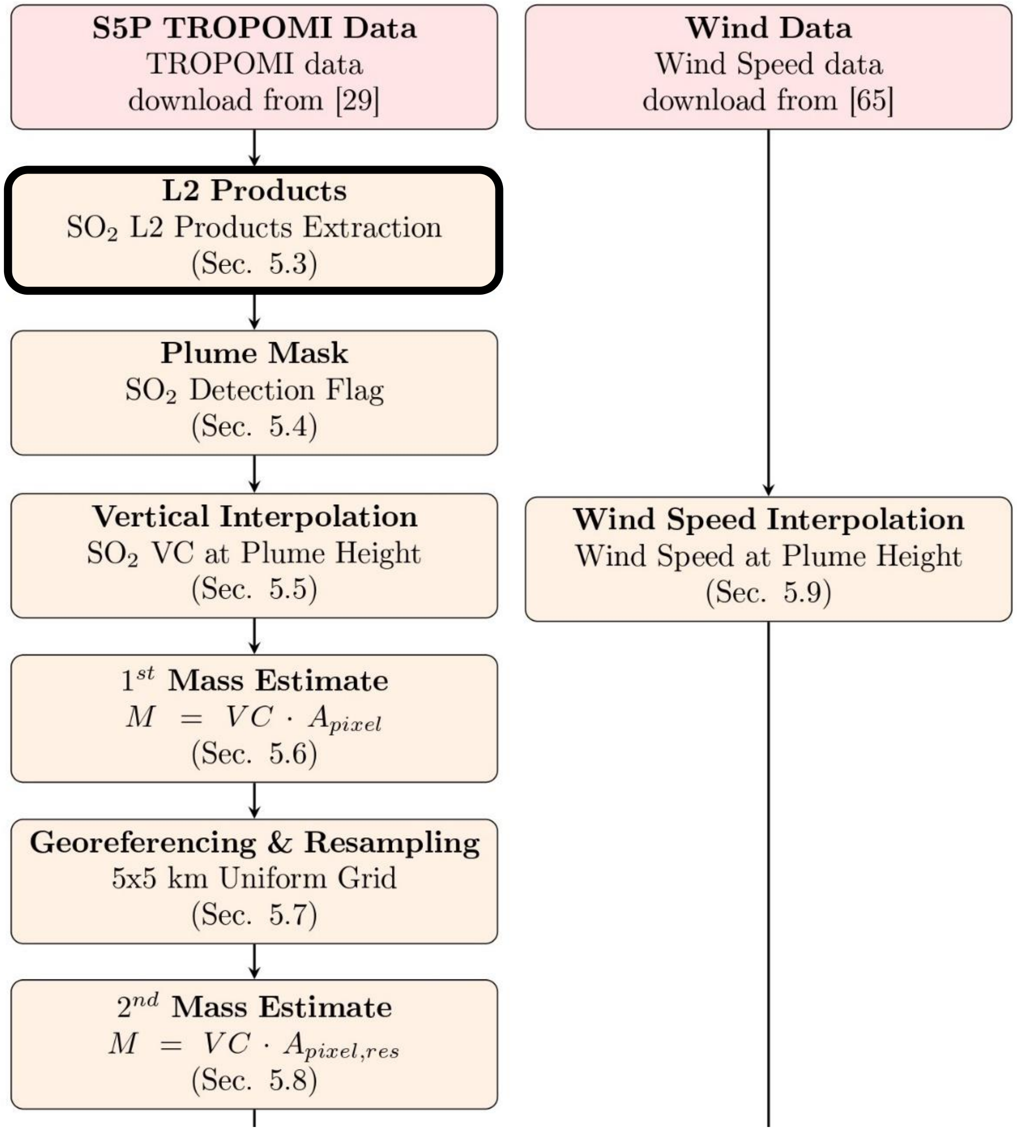
Extracted **L2 Products**:

sulfurdioxide_total_vertical_column_1km,
sulfurdioxide_total_vertical_column_7km,
sulfurdioxide_total_vertical_column_15km

surface_altitude

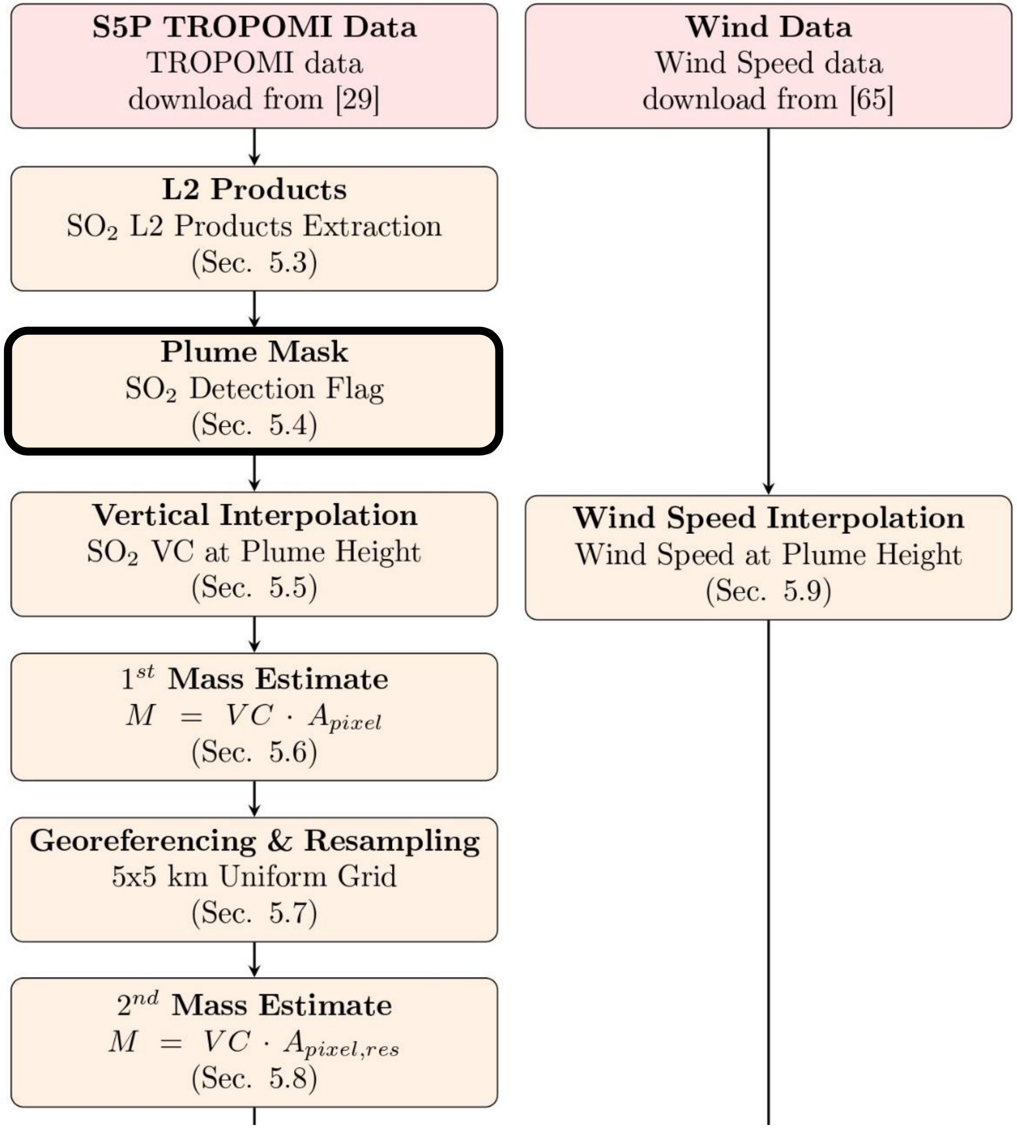
sulfurdioxide_detection_flag

sulfurdioxide_layer_height



Boolean variable indicating whether SO_2 has been detected:

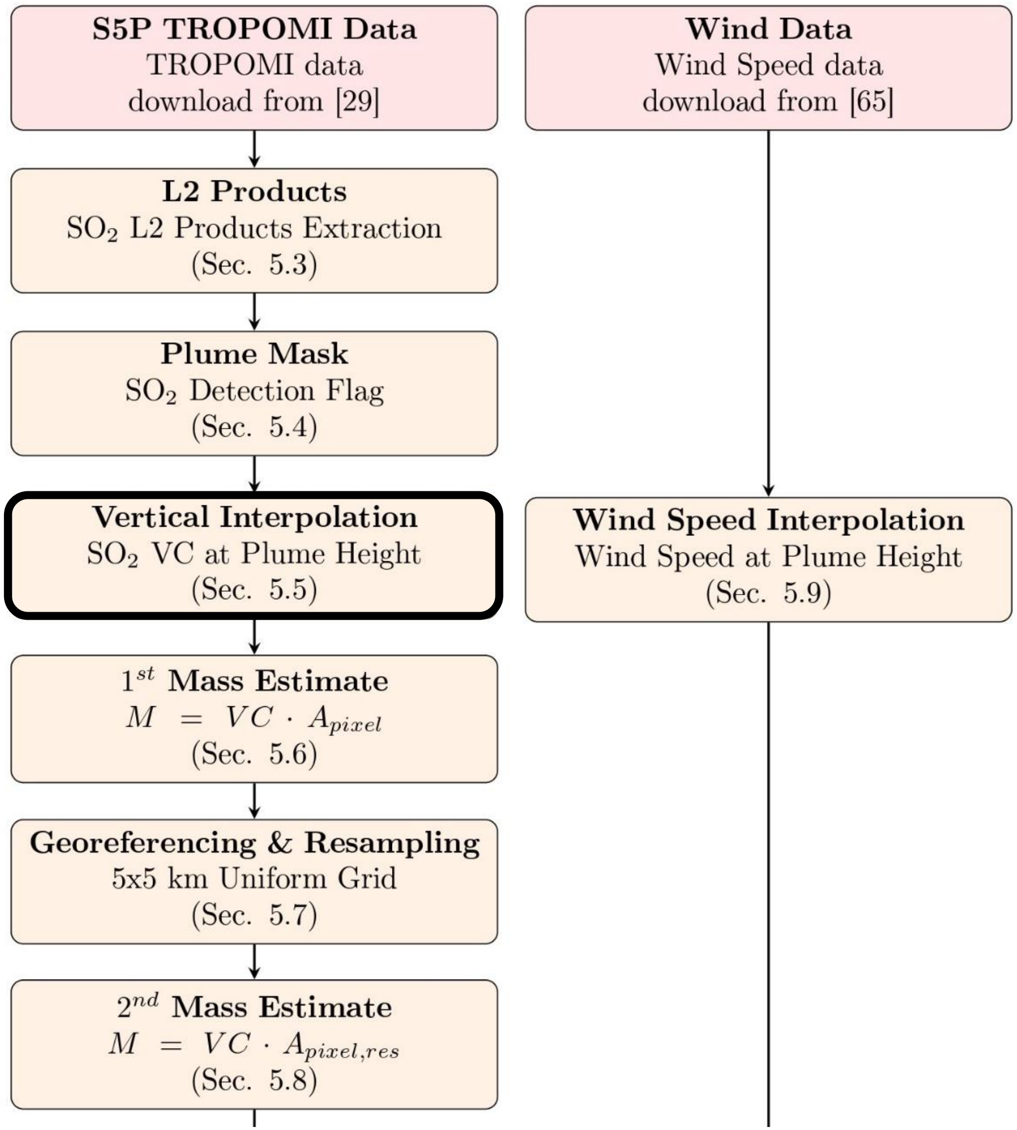
- 0: No detection
- **1: Weak detection**
- **2: Clear detection**
- 3: Anthropogenic SO2
- 4: False-positives



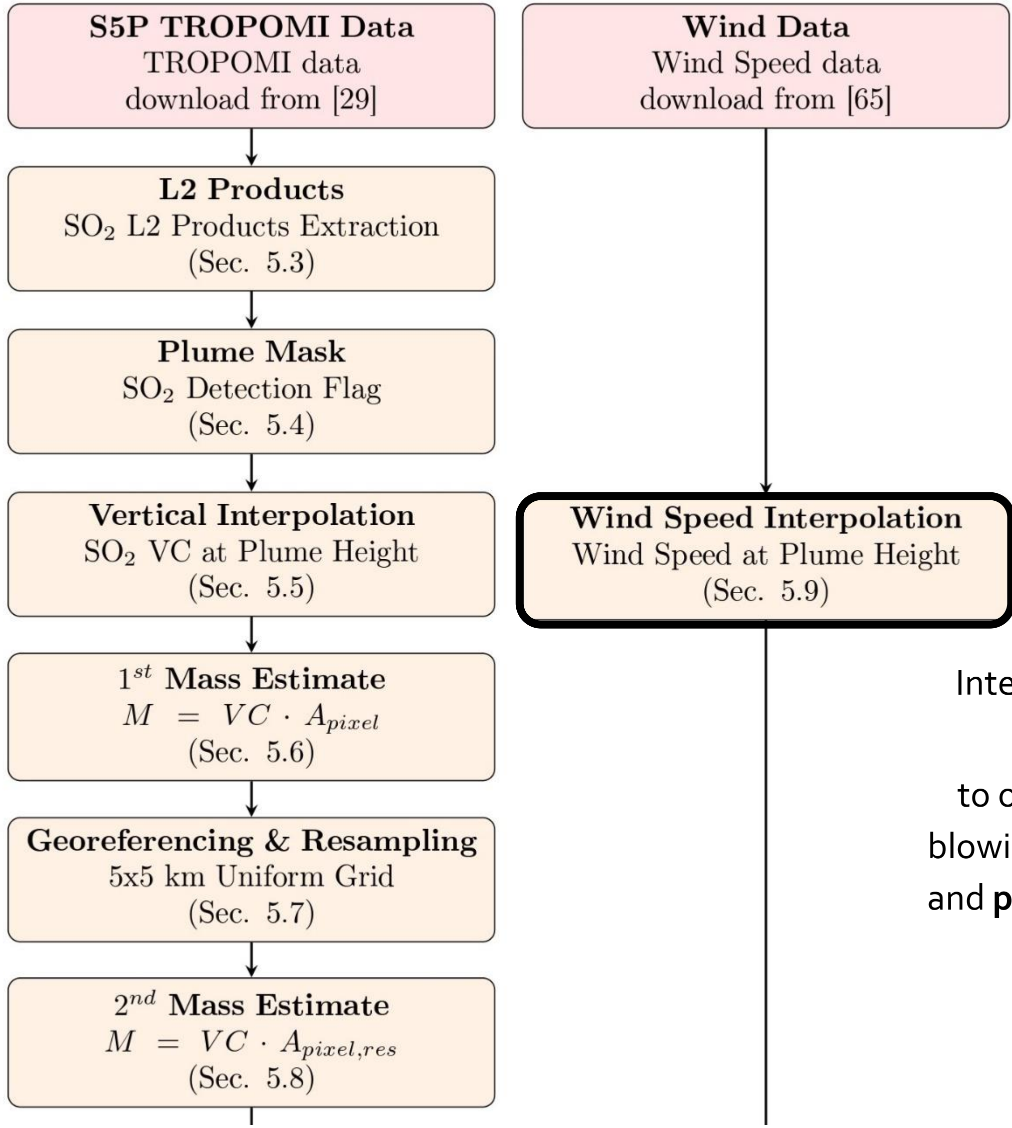
Developed Algorithm

Interpolation between the 3 distinct data matrices provided:

- **1 km**: planetary boundary layer, depends on **DEM**
- **7 km**: middle troposphere
- **15 km**: lower stratosphere



Developed Algorithm

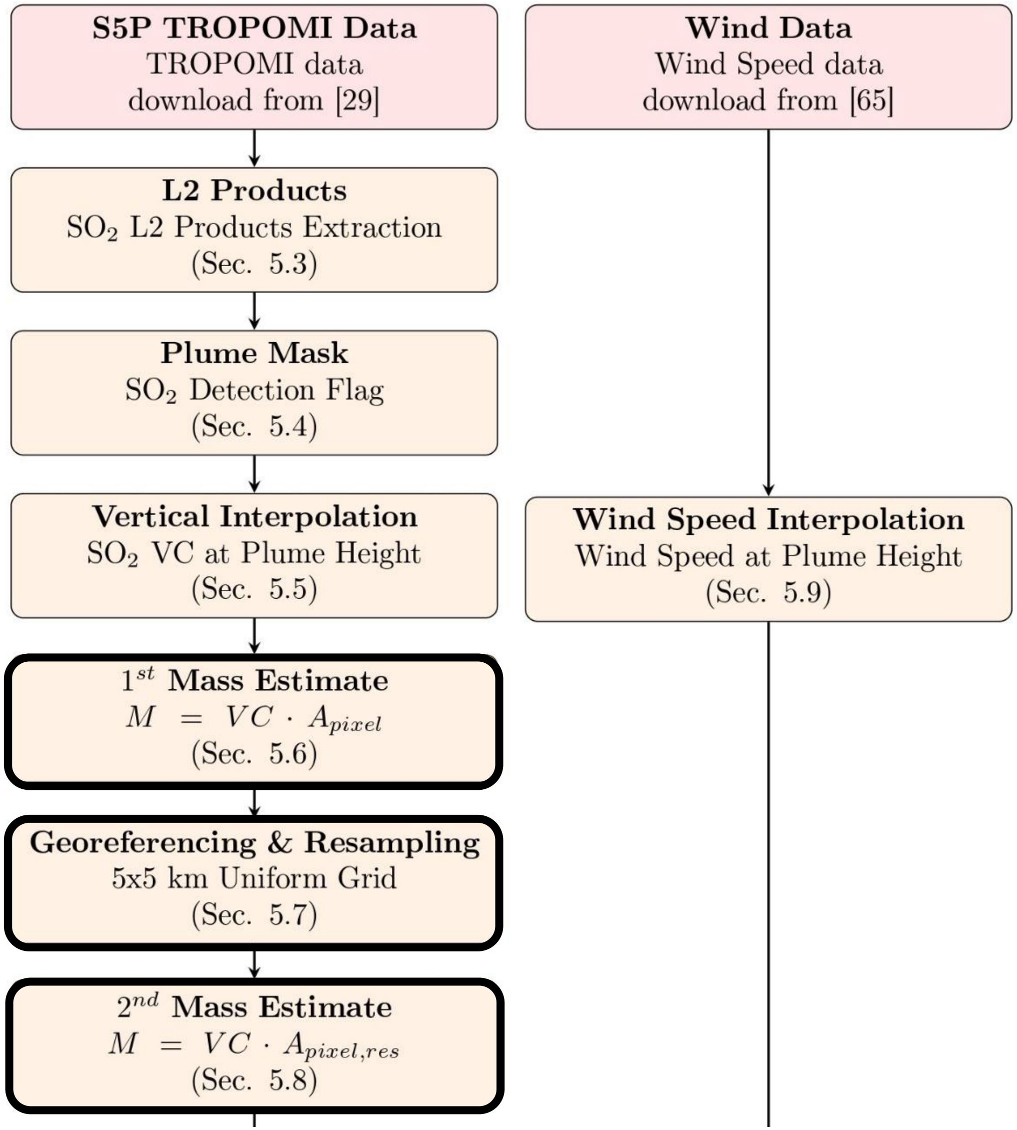


Interpolation of wind values at mean plume altitude,

to obtain a **single scalar value** blowing **radially** outward the vent and **perpendicular** to each pixel in the circular transects.

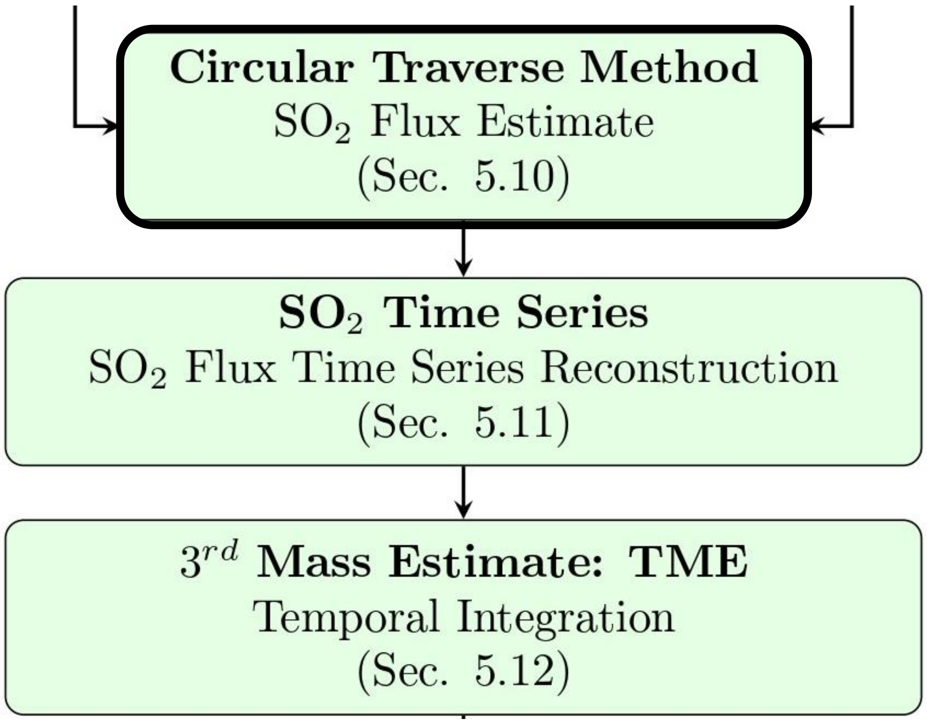
Developed Algorithm

TROPOMI spatial resolution:
5.5 km across-track
3.5 km along-track
↓
Projection of the distorted swath onto a **uniform Cartesian grid**
+
Application of **1DU threshold** to eliminate residual noise
↓
Resampled spatial resolution:
5 km x **5 km**



Transect = virtual cross-section drawn perpendicular to the transport axis of the plume.

Generation of **concentric circular transects** (radii starting from 5 km) around the vent.



The **mass flux of SO2** is calculated by integrating the SO2 VC along the transect, multiplied by the perpendicular component of the wind vector.

$$F_r = v_{\text{wind}} \cdot L_{\text{pixel}} \cdot \sum Y_{\text{plume}}$$

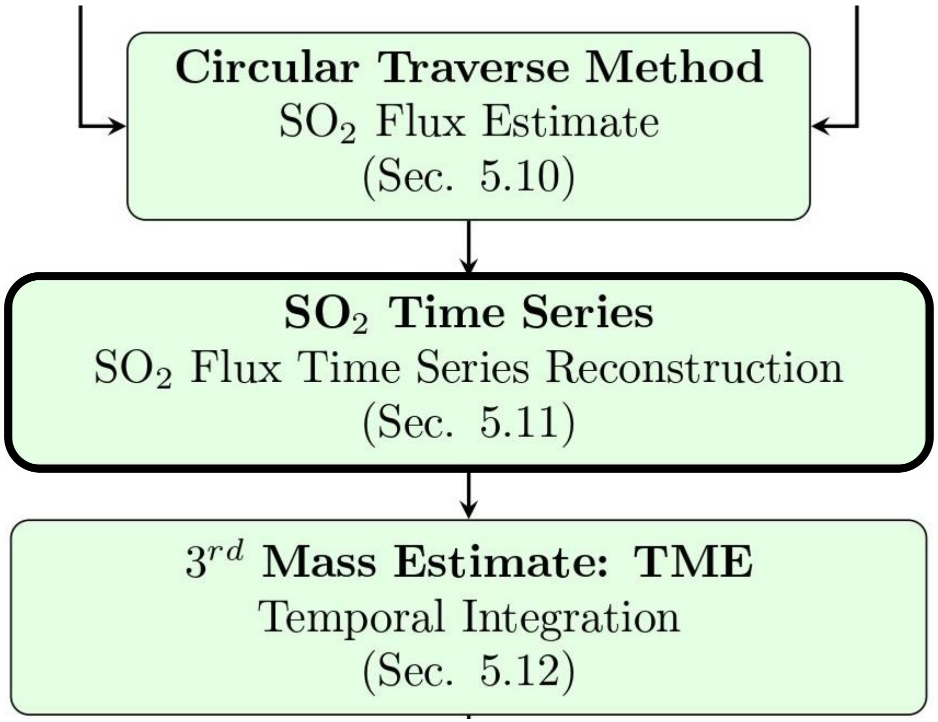
Optimised for plumes with **simple, linear geometries**

Developed Algorithm

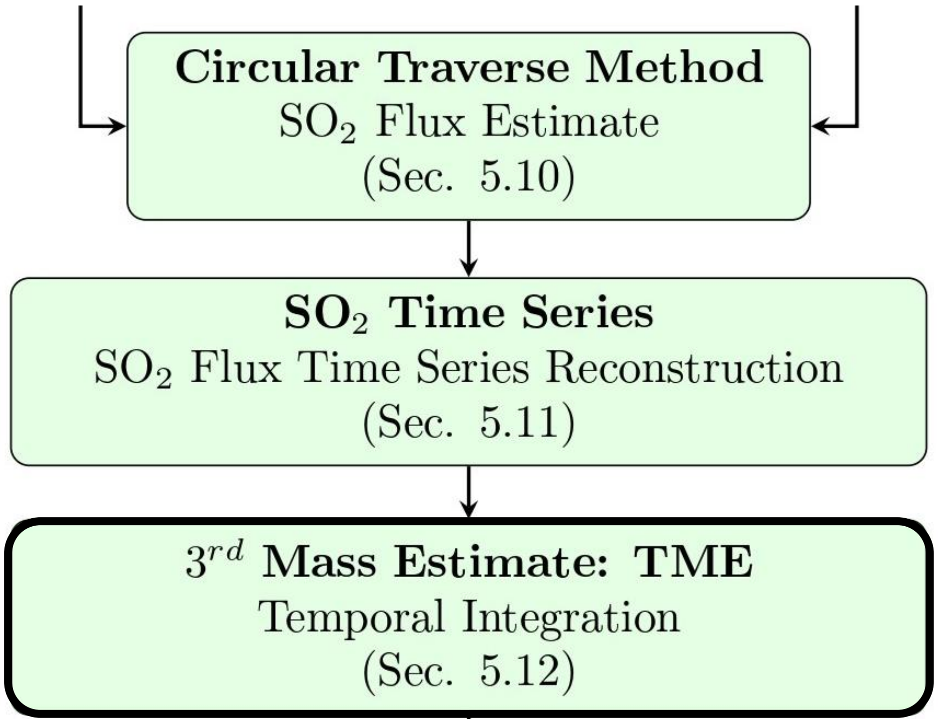
- Estimation of **SO2 Flux**
  - Reconstruction of **SO2 Flux Time Series:**

$$t_{emission} = t_{map} - t_{travel}$$

$$t_{travel} = \frac{r}{v_{wind}}$$



Developed Algorithm



Total Mass Erupted:

integral of the reconstructed SO2 flux over the observed event duration

ETNA

Italy

(37.752° N, 14.995° E;
3403 m a.s.l.)

2-3 June 2025

NYAMULAGIRA

Democratic Republic of Congo

(1.408° S, 29.200° E;
3058 m a.s.l.)

7 December 2025

HAYLI GUBBI

Ethiopia

(13.511° N, 40.713° E;
493 m a.s.l.)

23 November 2025

ETNA, Italy

02 June 2025

SETUP

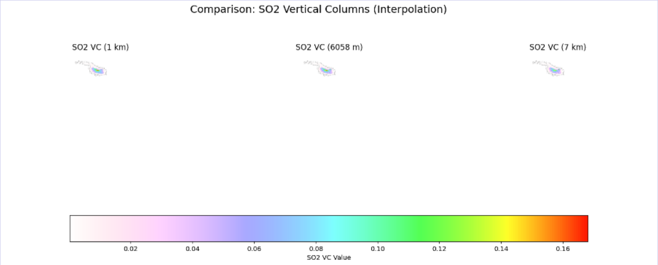
- TROPOMI image and wind data
- 37.752° N, Lon: 14.995° E
- UTM projection: zone 33N

EXTRACTED & INTERPOLATED VALUES

- Mean plume altitude: 6 km
- Wind speed: 2.56 m/s

CIRCULAR TRAVERSE METHOD

- Radial distance: 110 km
- Observation window: 11 h



03 June 2025

SETUP

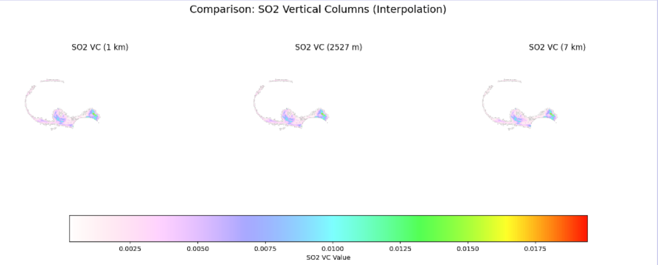
- TROPOMI image and wind data
- 37.752° N, Lon: 14.995° E
- UTM projection: zone 33N

EXTRACTED & INTERPOLATED VALUES

- Mean plume altitude: 2.5 km
- Wind speed: 4.69 m/s

CIRCULAR TRAVERSE METHOD

- Radial distance: 600 km
- Observation window: 30 h

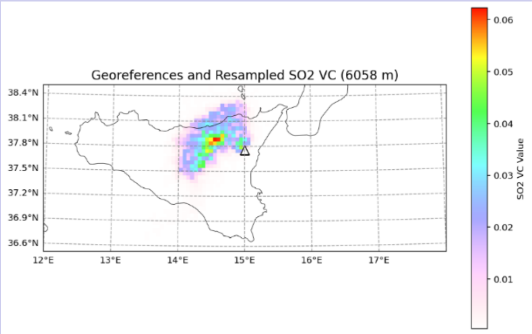


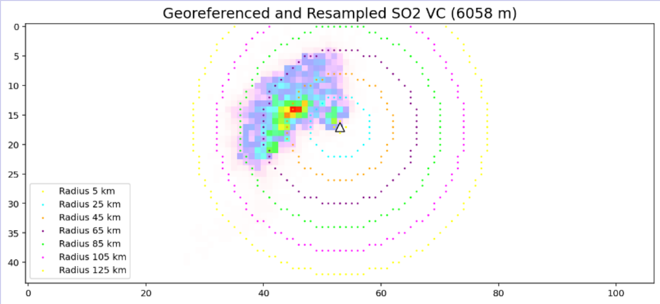
ETNA, Italy

02 June 2025

MASS CONSERVATION

- Post-resampling: 10 kt
- TME: 9.5 kt

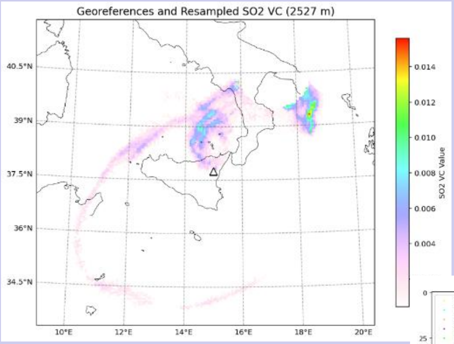


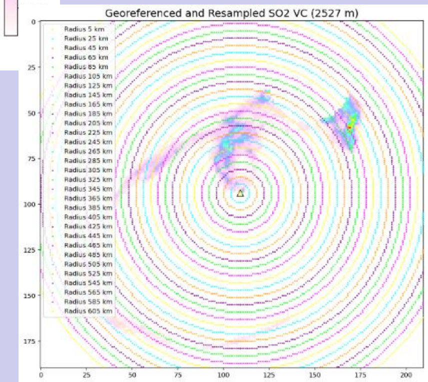


03 June 2025

MASS CONSERVATION

- Post-resampling: 14 kt
- TME: 14 kt

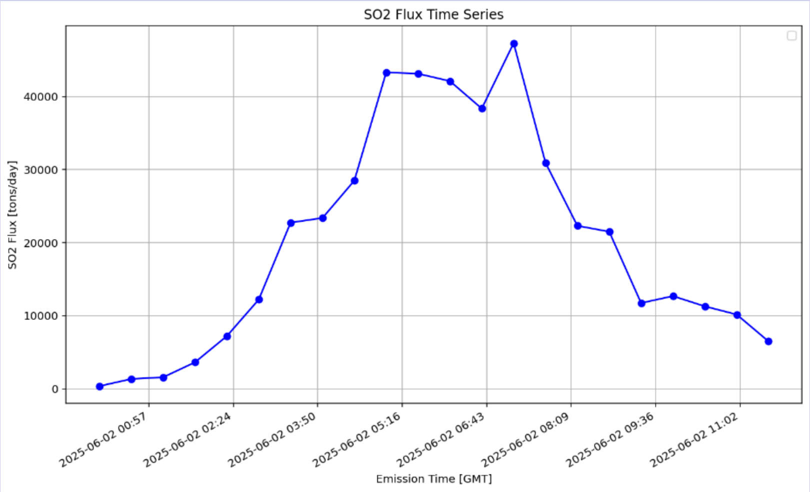




ETNA, Italy

02 June 2025

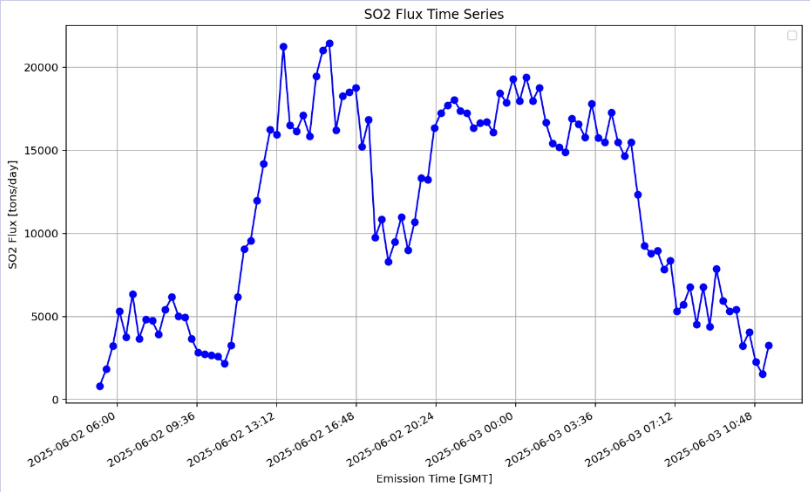
EMISSION TIME-SERIES



Classic paroxysmal event
with a peak of >40 kt/d around 5.30 a.m.

03 June 2025

EMISSION TIME-SERIES

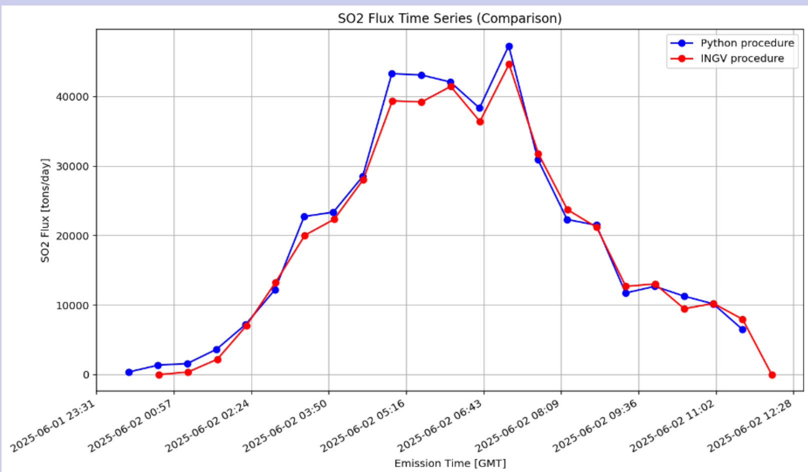


Prolonged, high-intensity degassing plateau.

ETNA, Italy

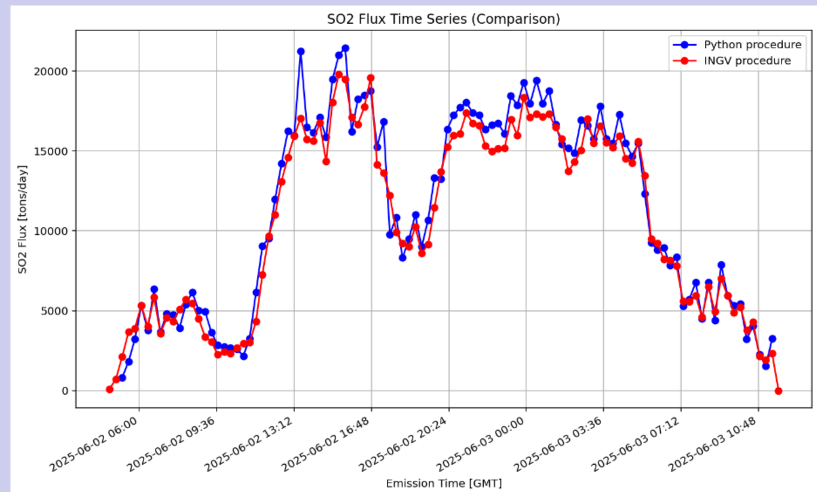
02 June 2025

EMISSION TIME-SERIES: VALIDATION



03 June 2025

EMISSION TIME-SERIES: VALIDATION



- Successful **reconstruction of the emission time-series**, reflecting realistic eruptive dynamics.
- Strong **quantitative agreement** with the established, supervised INGV procedure.

NYAMULAGIRA, DRC

07 Dec 2025

SETUP

- TROPOMI image and wind data
- 1.408° S, Lon: 29.200° E
- EQC projection

EXTRACTED & INTERPOLATED VALUES

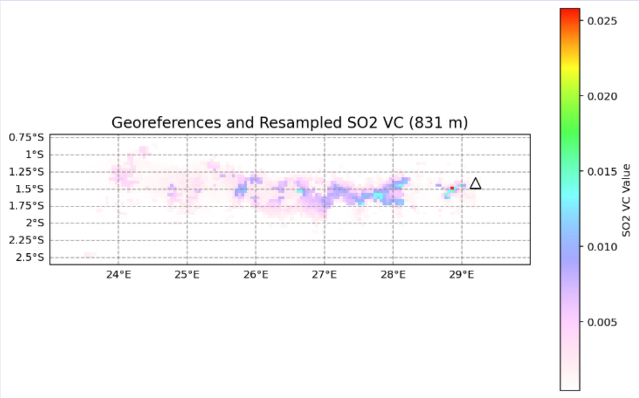
- Mean plume altitude: 0.8 km
- Wind speed: 3.1 m/s

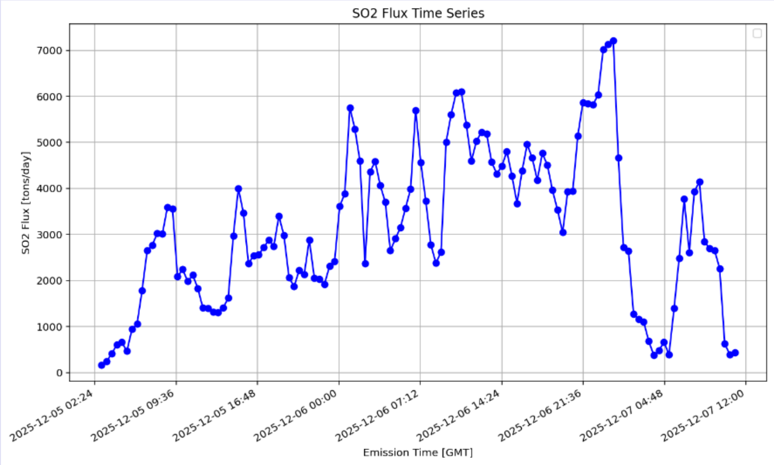
CIRCULAR TRAVERSE METHOD

- Radial distance: 630 km
- Observation window: 56 h

MASS CONSERVATION

- Post-resampling: 7.4 kt
- TME: 7.3 kt





Prolonged effusive degassing

HAYLI GUBBI, Ethiopia

23 Nov 2025

SETUP

- TROPOMI image and wind data
- 13.511° N, Lon: 40.713° E
- EQC projection

EXTRACTED & INTERPOLATED VALUES

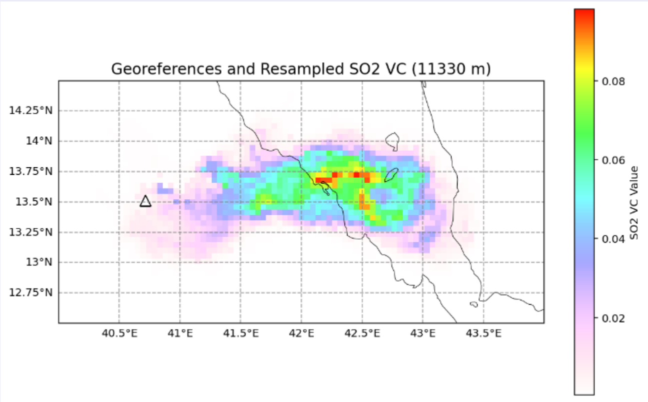
- Mean plume altitude: 11.3 km
- Wind speed: 30.13 m/s

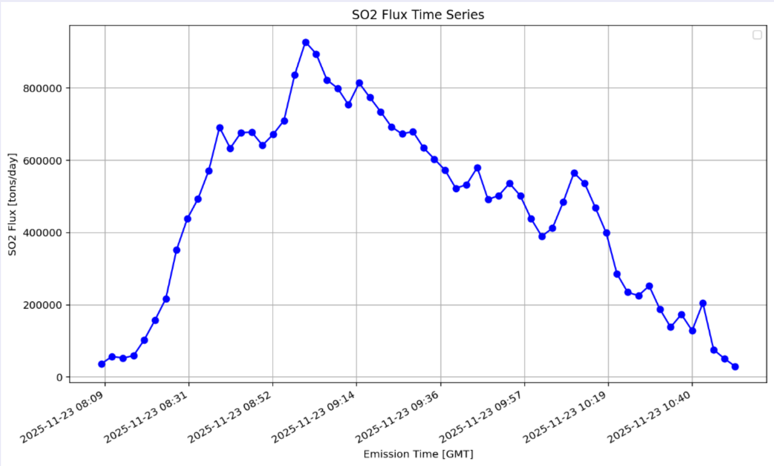
CIRCULAR TRAVERSE METHOD

- Radial distance: 300 km
- Observation window: 3 h

MASS CONSERVATION

- Post-resampling: 53.3 kt
- TME: 52.5 kt





Massive stratospheric injection

Conclusions

- **Novel automatic tool**: Development, validation and application of a new Python-based algorithm to retroactively reconstruct SO_2 emission time-series.

- **Global Applicability**: Crucial resource for observing remote and unmonitored volcanic areas.

- **High Adaptability**: Successful validation across diverse physical scenarios.

- **Robustness**: Demonstrated validity in terms of mass conservation.

- **Enhanced Accuracy**: Essential recover of SO_2 masses otherwise lost due to satellite geometric distortion thanks to georeferencing and spatial resampling.

Future Developments

- **Full Catalogue Automatisation**: Implement auto-retrieval for TROPOMI L2 products, wind data and dynamic bounding boxes.

- **Threshold Optimisation**: Evolve from a static 1 DU limit to an adaptive model, recovering diluted plume edges (early emissions).

- **Pixels Pre-selection**: Restrict flux estimations to proximal transects (< 6 hours of transport) to avoid SO_2 diluition effects (H_2O recombination).

- **Ground-Based Cross-Validation**: Direct comparison with INGV Etna FLAME UV camera network to quantify uncertainties.

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EGU26 GENERAL ASSEMBLY

Abstract accepted for a poster presentation at the European Geosciences Union (EGU) General Assembly 2026, in Vienna.

THANK YOU FOR YOUR ATTENTION

Elisa Rosella