

Determination of SO₂ fluxes from Mt. Etna exploiting S5P-TROPOMI and ground-based UV camera observations

Maddalena Dozzo^{1,2,*}, Alessandro Aiuppa¹, Steffen Beirle³, Marcello Bitetto¹, Dario Delle Donne², Giovanni Lo Bue Trisciuzzi¹, Thomas Wagner³, Simon Warnach^{3, now at 4}, Gaetana Ganci²

¹ Università degli Studi di Palermo, Via Archirafi 22, 90123, Palermo, Italy; ² Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00143, Roma, Italy; ³ Max-Planck-Institut für Chemie, Hahn-Meitner-Weg 1, 55128, Mainz, Germany; ⁴ EUMETSAT, Darmstadt, Germany

*maddalena.dozzo@ingv.it

MOTIVATIONS

Sulfur dioxide (SO₂) is sourced by degassing magma in the shallow crust; hence its monitoring provides information on the rates of magma ascent in the feeding conduit and the style and intensity of eruptions, ultimately contributing to volcano monitoring and hazard assessment. The aim of this work is to retrieve the SO₂ fluxes time series exploiting the TROPOMI imaging spectrometer, launched in 2017, onboard the Sentinel-5 Precursor satellite, which provides atmospheric column measurements of sulfur dioxide and other gases with an unprecedented spatial resolution (pixel size of 5.5 km × 3.5 km at nadir) and daily revisit time with the aim of comparing them with ground-based measurements, obtained from a permanent UV camera system. SO₂ fluxes are determined by the plume traverse method (Theys et al., 2019), primarily by estimating the plume height from the wind direction. Our approach proves advantageous thanks to the division of the plume into circular rings and sectors, which allows for immediate retrieval of the wind speed. Conversely, wind at different altitudes in the same direction can lead to high standard deviation values. The Mount Etna volcano (Italy) is taken as a case of study, which emits SO₂ with fluxes ranging typically between 500 and 5000 t/day. We compare our results with those available in the literature, focusing on ground measurements for validation, with Etna volcano being an ideal case study due to the presence of a consistent ground monitoring network. This work, if extending the method to other volcanoes, might contribute to obtaining a response to unrest/eruption at volcanoes worldwide.

STUDY AREA

We study the eruptive events occurred at Mount Etna volcano (Italy).

Mt. Etna is an open-conduit volcano, which consistently exhibits persistent degassing, primarily maintained by the passive release of gas from shallow convecting magma. This typically includes mild intra-crater Strombolian explosive activity. However, this routine activity is often interrupted by effusive eruptions and occasionally by violent paroxysmal explosive events. We focused on the 2018-2019 period, considering an area large enough to contain the major part of the plume.



Fig. 1. Study area around Mt. Etna

DATA

Sentinel-5P is a sun-synchronous, quasi-polar low-Earth orbit (824 km) satellite, which has an almost full-earth-surface coverage daily. It has a swath of 2600 km and an orbital cycle lasting 16 days, i.e., 14 orbits per day, and 227 orbits per cycle on average. TROPOMI acquires data in four different spectral regions (ultraviolet, visible, near and short-wave infrared) that allow the observation of SO₂, among many other gases (O₃, NO₂, CO, CH₄, HCHO, aerosols). This sensor has a pixel size near the nadir equal to 3.5 km × 5.5 km.

The Level 2 TROPOMI data, provided by the Copernicus Browser (<https://browser.dataspace.copernicus.eu>), has been downloaded and exploited for this study.

As regards the meteorological data, we used ECMWF ERA5 hourly data regridded to a regular lat-lon grid of 0.25 degrees (<https://cds.climate.copernicus.eu>).

Finally, we compared our results with those available from the ground, retrieved from a permanent UV camera system located at Montagnola (~ 2600 m a.s.l.).

METHODS

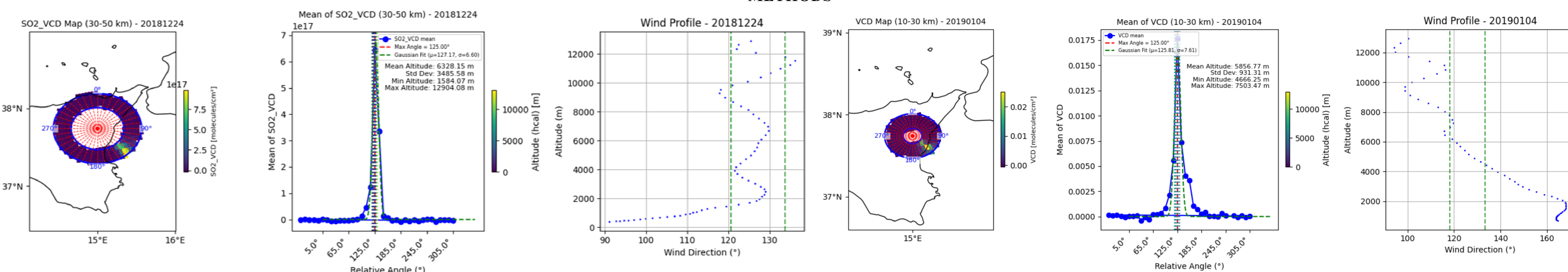


Fig. 2. 1) On the left: 30-50 km ring on VCD related to 24.12.2018 eruption. In the middle: VCD mean, calculated in each section, with the red line representing the max value (thus the direction of the plume). Wind heights are plotted within 1 sigma compared to the max. On the right: wind profile in the same date, from ERA5 dataset. In this example the calculated plume height is equal to 6328 ± 3485 meters; 2) Another example considering the 10-30 km ring related to the 04.01.2019 eruption, showing a lower standard deviation. In this case the plume altitude is estimated to be 5857 ± 931 meters.

1. Filtering of Sentinel-5P TROPOMI OFFL Level 2 data for latitude and longitude ranges of Etna;
2. Correction of Slant Column Densities (SCDs) from Air Mass Factor retrieval (AMF), to derive the Vertical Column Densities (VCDs). To calculate the AMF, we assumed that it is consistent with the averaging kernel (AK) computed from the a priori sulfur dioxide profile; therefore, we calculated the AMF as the weighted sum of the AK values, using the a priori profile as weights (i.e., $AMF = \sum_l AK_l \cdot x_l / \sum_l x_l$), where x_l is the a priori SO₂ concentration in layer l (Eskes & Boersma, 2003; Beirle et al., 2023);
3. Plume height estimation using wind direction and comparison with heights from the VONA (<https://www.ct.ingv.it>) and SEVIRI (using the inverse of the Max Planck's law and the channel 9);
4. Definition of 20 km thick ring in 4 different ranges (10-30, 30-50, 50-70, 70-90 km from the volcano) and correction for the background;
5. Removal of cases without a clear plume (comparison between SO₂ max and the std of the background), cases which has NaN values in the angular sector correspondent to the wind direction and those where sigma is higher than 40;
6. Application of the Cross Sectional Method (Theys et al., 2019) in the ring;
7. SO₂ fluxes calculation (in t/day) and comparison with ground-based data.

RESULTS

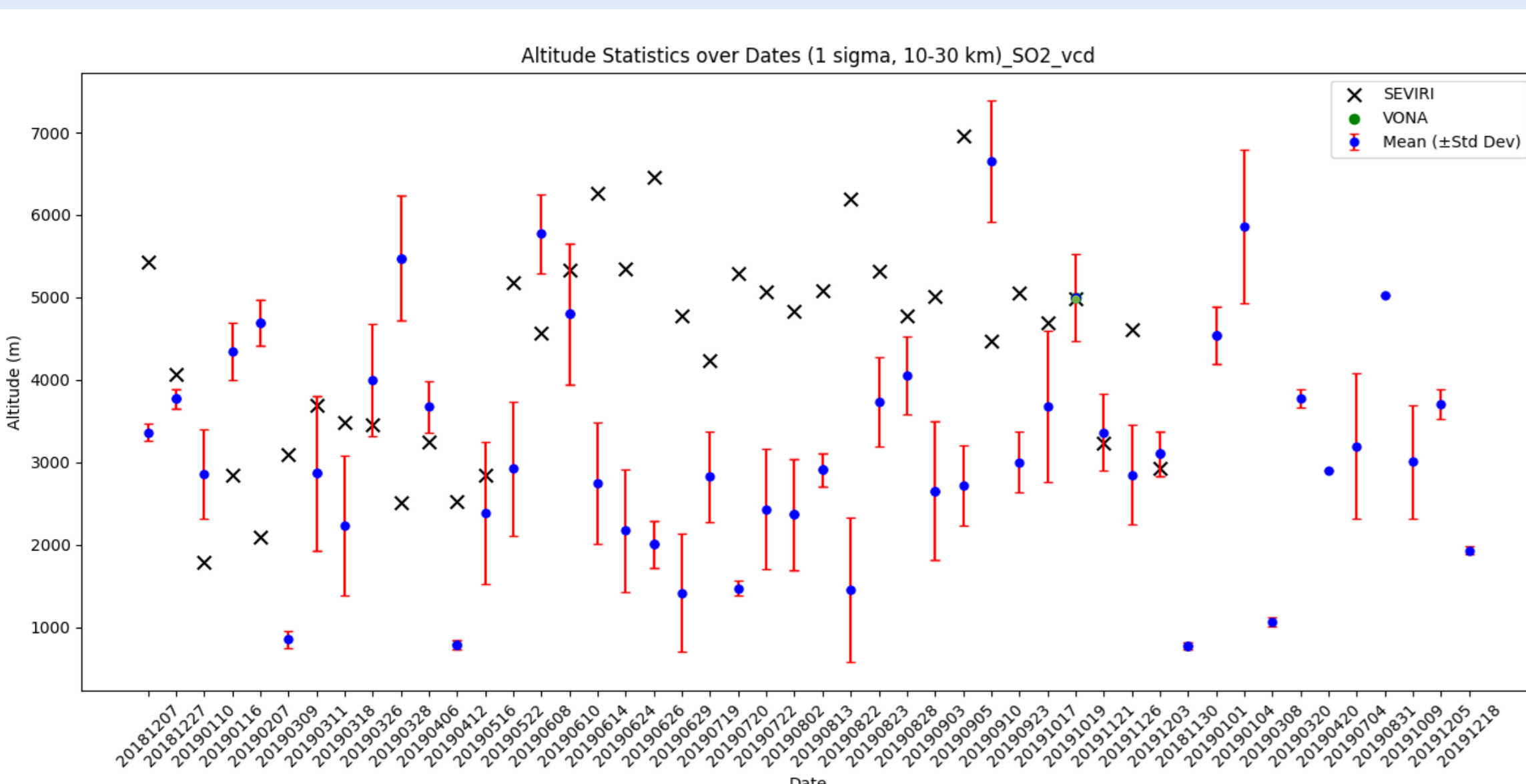


Fig.3. Time series of the mean plume altitude ± standard deviation (lower than 1 km), retrieved from the wind direction in the range 10-30 km for the period 2018-2019, compared to heights from VONA and SEVIRI.

$$SO_2 \text{ Flux} = VCD \cdot M \cdot L \cdot v$$

Where:

- VCD = vertical column density [mol/m²]
- M = molar mass of SO₂ [g/mol]
- L = arc length [m]
- v = wind speed [m/s]

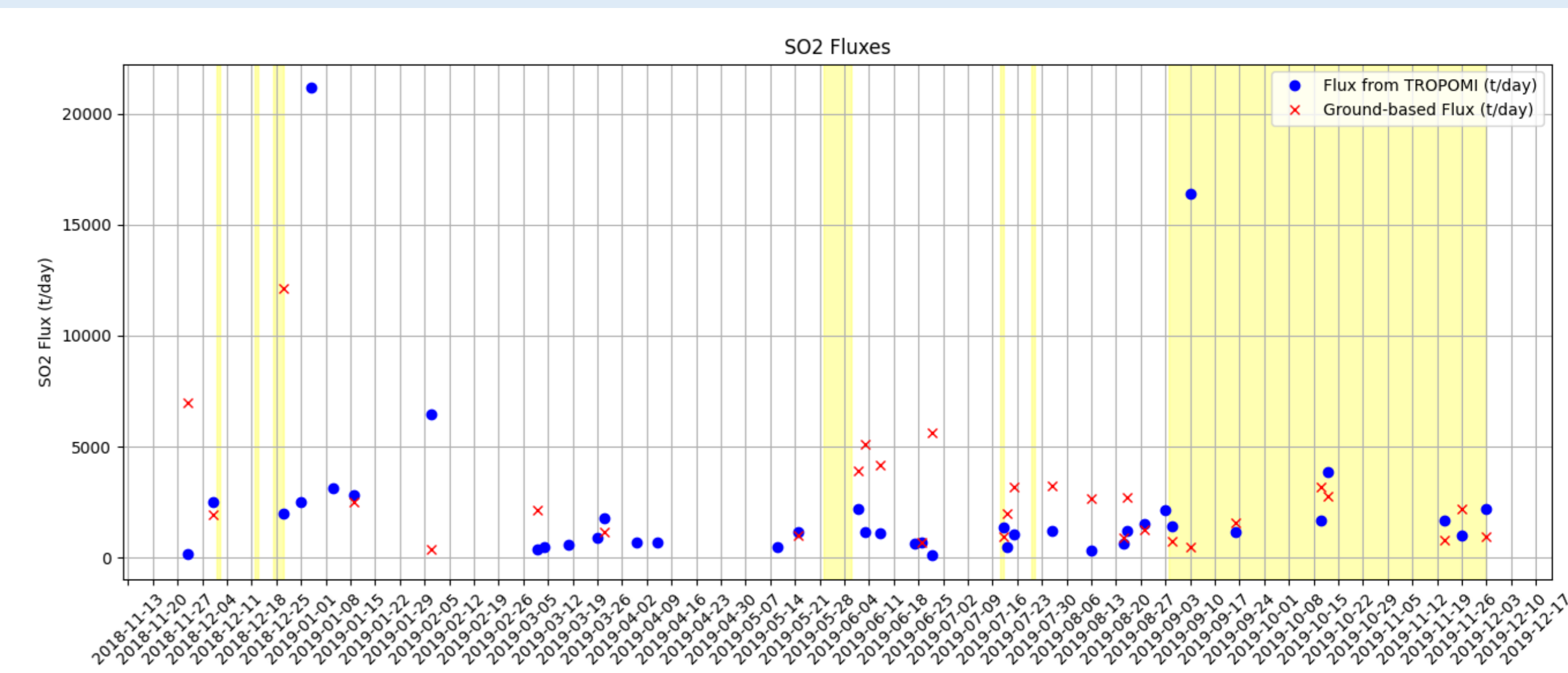


Fig.4. Time series on the same dates in the range 10-30 km of SO₂ fluxes in t/day, calculated from TROPOMI (blue dots) and from the ground (red crosses). The days of eruption are highlighted in yellow.

CONCLUSIONS

- The presence of different heights is well reflected by the standard deviation uncertainty.
- Percentage of cases where the standard deviation is less than 1 km (after the removal of cases without a clear plume, cases which has NaN values in the angular sector correspondent to the wind direction and those where sigma is higher than 40) : ~20 % ;
- The mean difference with SEVIRI is 1890 m (considerations: SEVIRI is sensitive to the clouds over the plume and for the upper part of the plume, which leads to a systematic overestimation compared to TROPOMI; The effect of ash/ice on the measurement sensitivity of TROPOMI can lead to biases (underestimation) in the retrieved SO₂ heights (Guerrieri et al., 2023)).
- Quite good results from the comparison with VONA, but it is a small dataset.
- Our approach allows an immediate retrieval of the wind speed. However, there are some cases with high standard deviation values due to the presence of wind at different altitudes in the same direction;
- In general, SO₂ flux values measured by TROPOMI are lower than those from ground-based observations. However, the comparison may be unrepresentative due to the presence of multiple NaN values in the ground-based data and the limited size of the dataset.
- Overall, the method presented here allows for a rapid estimation of plume altitudes and therefore of the SO₂ fluxes. The main limitation concerns the presence of wind at different altitudes moving in the same direction. Discrepancies between the values of heights calculated from TROPOMI and those obtained with SEVIRI, together with the fluxes from TROPOMI compared to those measured from the ground will be the subject of targeted future investigations.

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