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TAKING THE PULSE OF OUR PLANET FROM SPACE

High resolution monitoring of volcano degassing with Sentinel-5P and integrated data analysis with Sentinel-2

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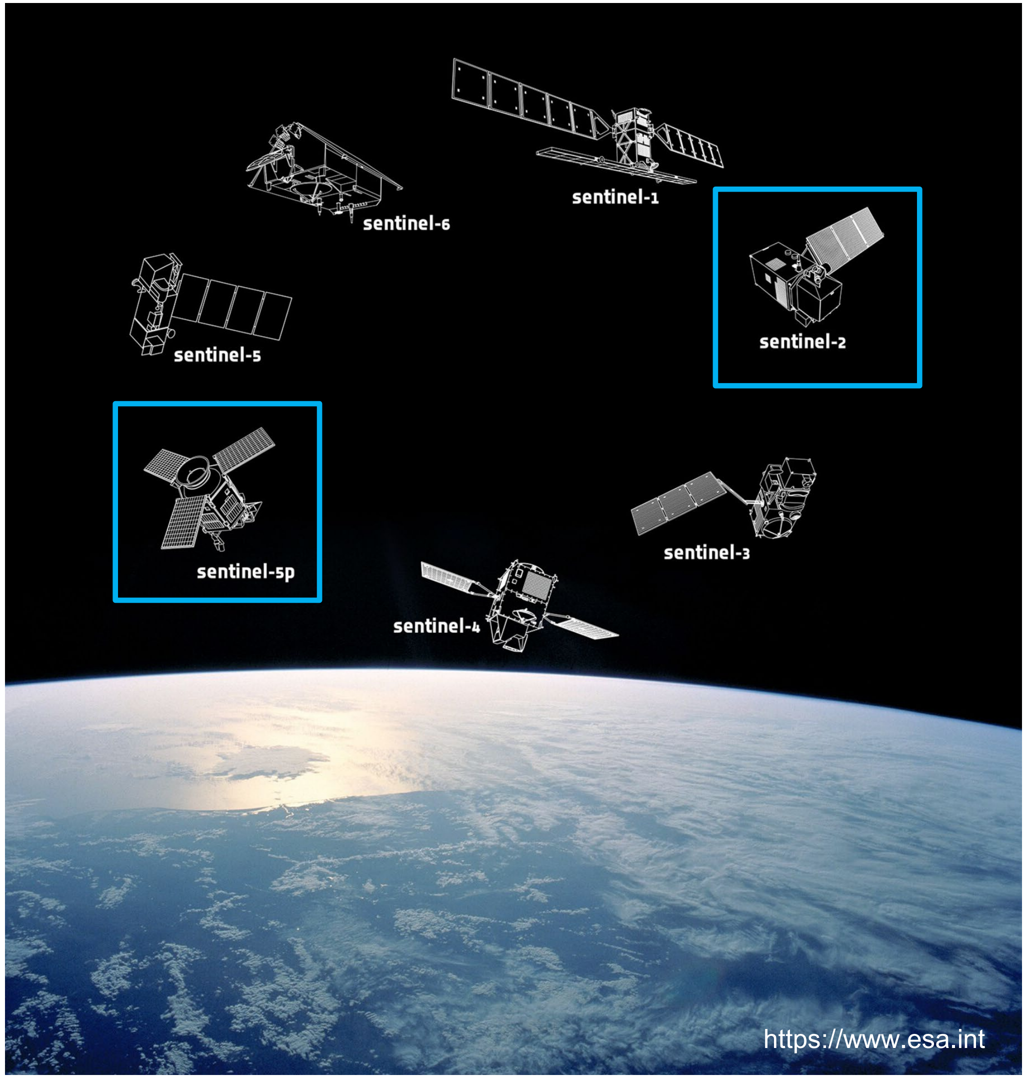
23/05/2022

Background and scientific goals



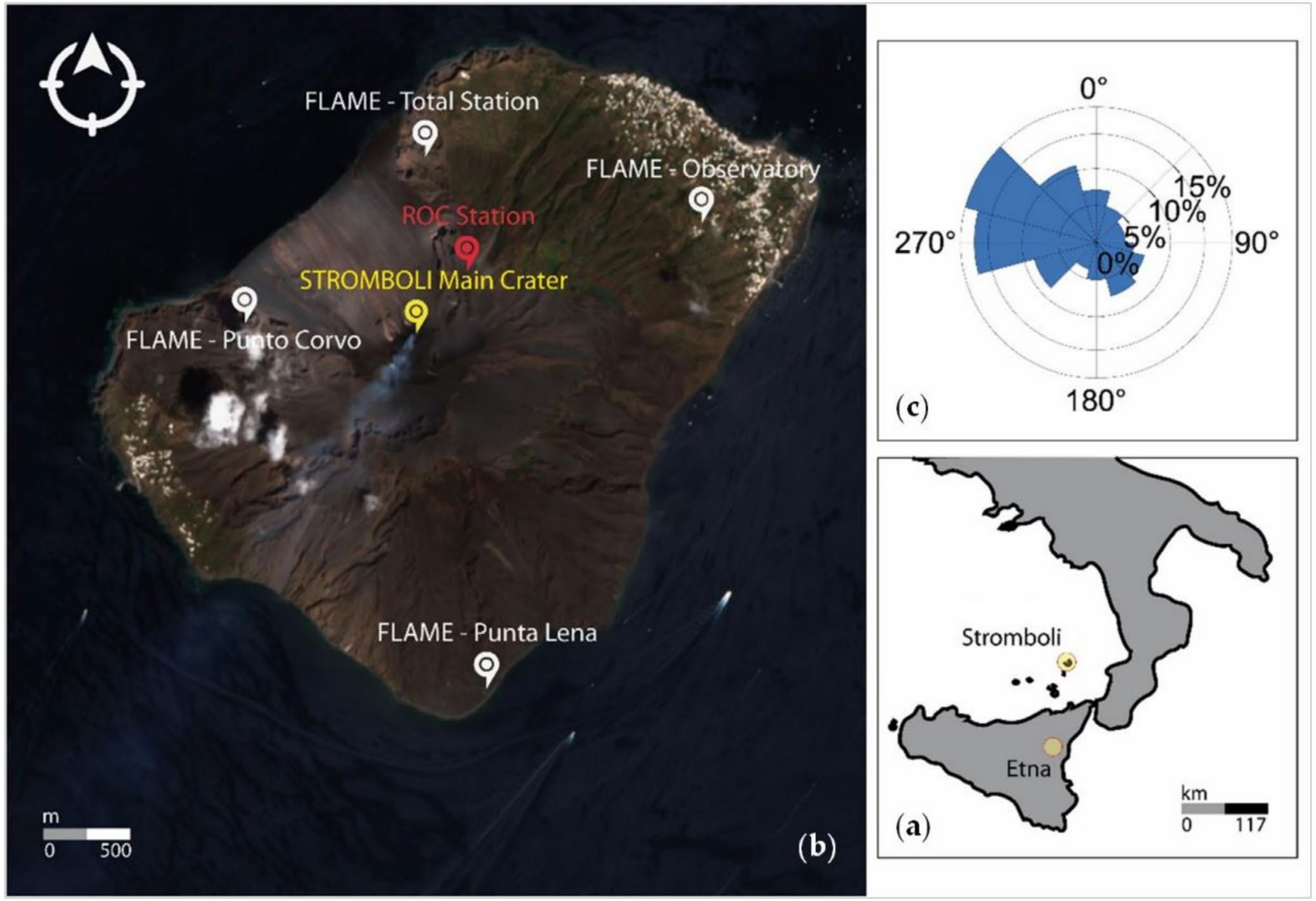
The Copernicus Sentinel missions together provide **a stream of complementary data** and **a combination of high-resolution observation capabilities** in different bands that few years ago were not yet available

If used in a coordinated way, **their data can upgrade scale and spatial/temporal resolution of investigations of small-sized volcanoes**, with violent and potentially hazardous eruptions

Our goals

- To demonstrate that the TROPOspheric Monitoring Instrument (TROPOMI) onboard **Sentinel-5 Precursor (Sentinel-5P)** has the suitable spatial resolution and sensitivity to carry out local-scale sulfur dioxide (SO_2) monitoring of small-size, nearly point-wise volcanic sources
- To showcase how the synergistic exploitation of Sentinel-5P data along with optical imagery acquired by the Multi-Spectral Instrument (MSI) sensor onboard **Sentinel-2** enables a better understanding of the situation on the ground and to distinguish periods of different volcano activity intensity
- To test a methodological workflow for TROPOMI SO_2 time series analysis and volcanic activity detection

Study area and ground-based sensor data



COFANO *et al.* 2021, doi:10.3390/S21216991

Stromboli volcano, southern Italy

- constant activity, with persistent degassing that may last for several days to years, leading to gas emissions comparable to large eruptions
- violent and explosive eruptions (a whole category of volcanoes is named after it) lasting a few minutes at most but recurring at various intervals (15 s long, with rates of ~13 explosions/hour)
- SO_2 emission rates are in the order of ~730 t/d
- equipped with ground-based monitoring network (e.g. ROC)

Why looking at SO_2?

- A proxy to study volcanic activity and its hazards (it is the most abundant gas involved, after water vapor and CO_2)
- SO_2 flux is often considered as a precursor to eruptions and a marker of major volcanic processes
- if considered in relation to other gases, can provide additional constraints to volcanic activity and degassing
- low background concentration in the atmosphere, hence relatively easy to detect away from anthropogenic sources

Sentinel-5P satellite and its TROPOMI sensor

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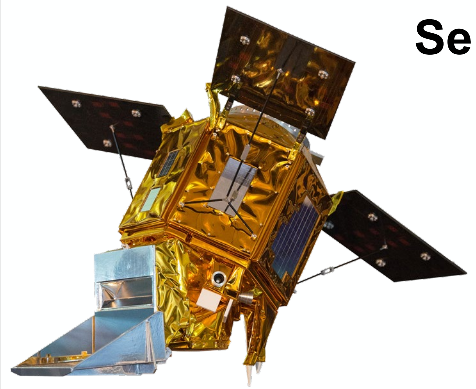
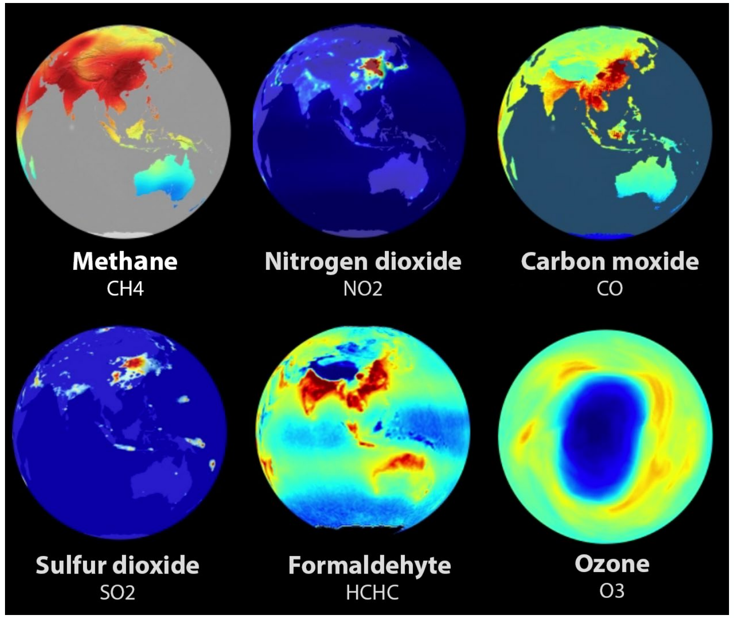
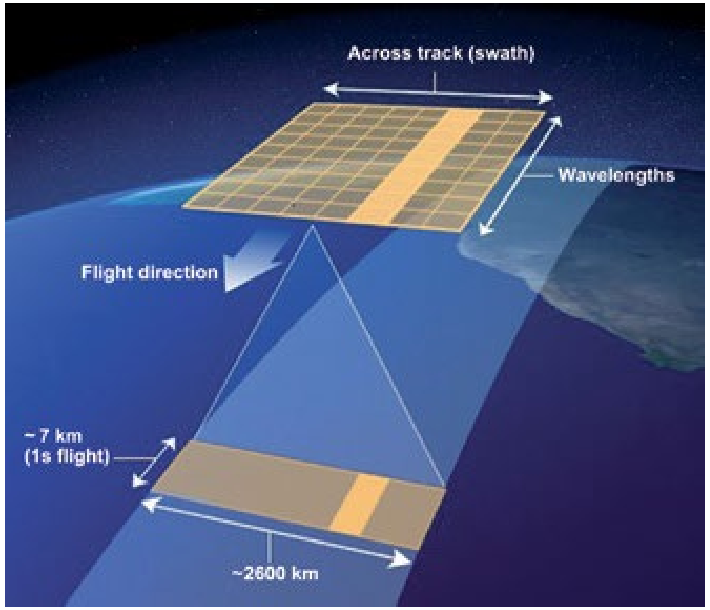


Sentinel-5P

- Launched on 13 Oct 2017 as a precursor to Sentinel-4 and Sentinel-5, operational since May 2018
- Sun-synchronous, quasi-polar low-Earth orbit (824 km)
- 16 days orbital cycle, though **daily global coverage is achieved** owing to the 108° across-track field-of-view and the use of multiple tracks





TROPOMI

- Acquires in UV, VIS, NIR and SWIR
- Allows observation of SO_2, and many other gases
- 2600 km swath width
- Pixel size near the nadir: **3.5 km × 7 km** (across- x along-track) until Aug 2019, then **3.5 km × 5.5 km**
- Achieved improvements vs. other SO_2 monitoring sensors:
  SO_2 emissions detection limit is a factor of 4 better than OMI; spatial resolution is better than OMI (13 km × 24 km); sensitivity to SO_2 variations is higher than IASI
- L2 SO_2 products are generated by the Royal Belgian Institute for Space Aeronomy (BIRA-IASB): raw data calibration and georeferencing; radiance and irradiance estimation; extraction of SO_2 concentrations from UV spectrum via Differential Optical Absorption Spectroscopy (DOAS) algorithms

TROPOMI SO_2 data analysis for Stromboli

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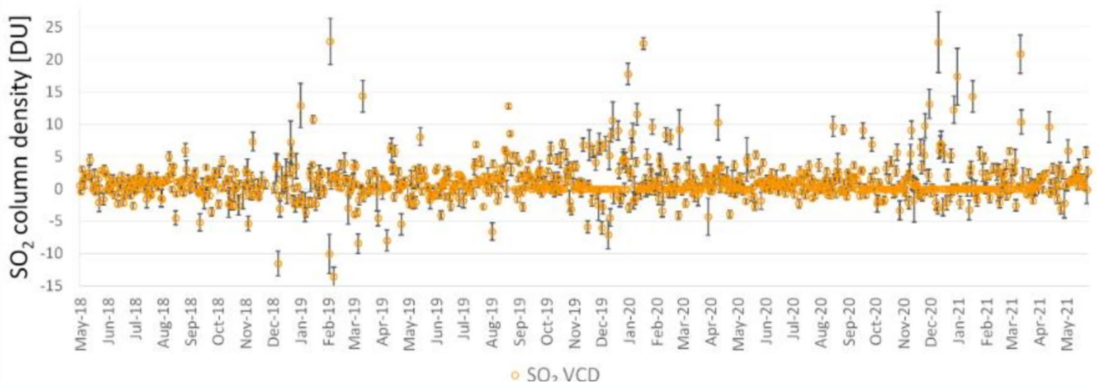
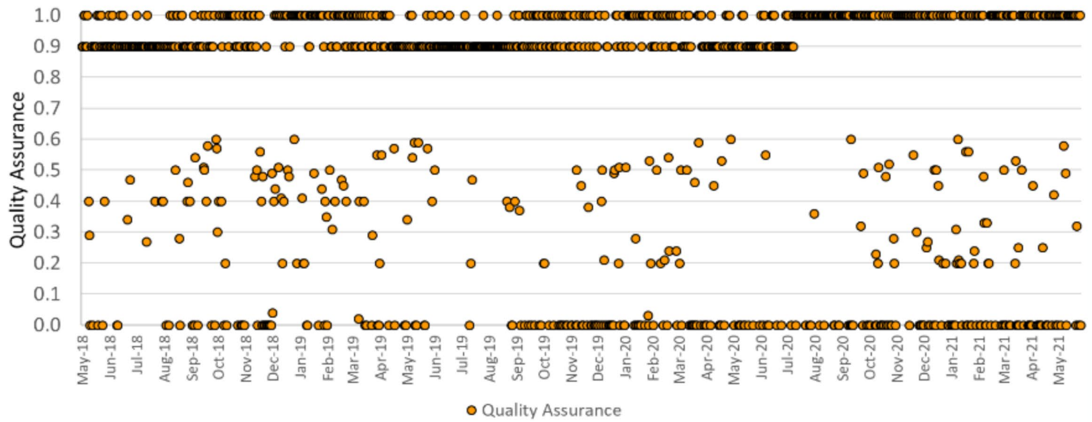
Input data: **1370 Level 2 SO_2 products** (netCDF-4 format)

Period: **6 May 2018 - 31 May 2021**

Time slot: 09:45–13:15 UTC





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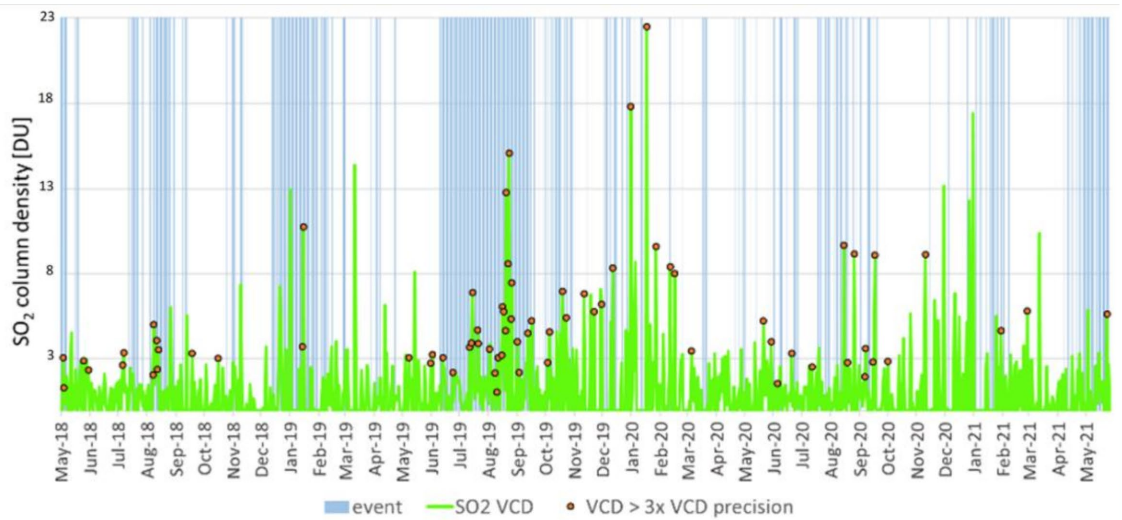
1) We **adapted NASA's Python scripts** originally aimed to read NO_2 products, and tailored them to extract time series of SO_2 and auxiliary information (e.g. quality index, standard deviation, cloud fraction) at given [lat,lon] inputs

2) We followed the recommendations by Mission Performance Centre (MPC) and Sentinel-5P Validation Team (S5PVT) to **quality filter the data**

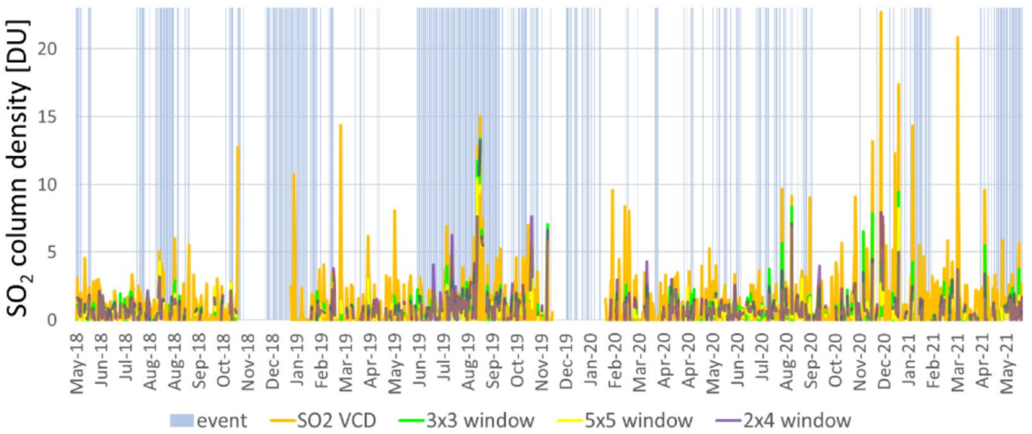


SO_2 vertical column density (VCD) observations after QA and outliers filtering, vs. periods of intense volcanic activity according to UNIFI's ROC ground sensor data

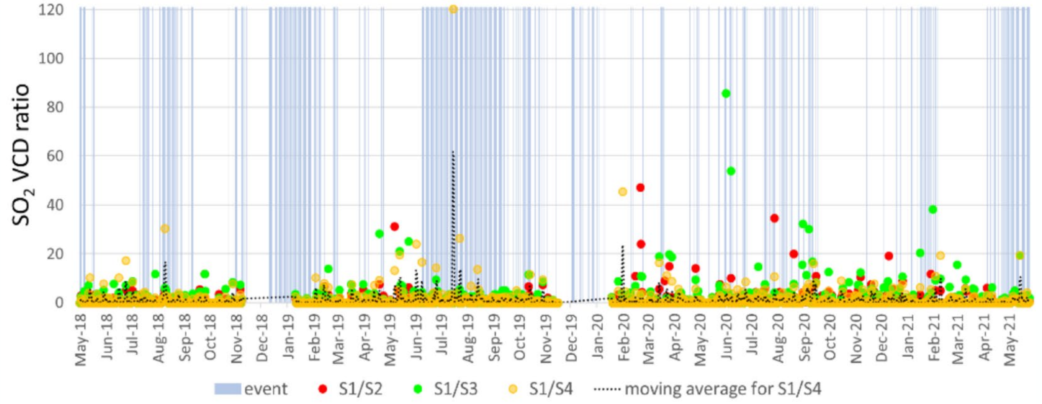
VDC in mole concentrations (mol/m^2) can be expressed in Dobson Units (DU), where 1 DU=2.69×10^{16} molecules/cm^2 (no. of molecules in atmospheric column per unit area)

Spatial averaging and ratioing

SO_2 VCD at the crater vs. averaging windows



SO_2 VCD ratios between crater and averaging windows



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3) Point-wise SO_2 data at the **main crater** [S1: 38.79°N, 15.21°E] were compared with observations at **averaging windows** [S2:3x3, S3:5x5, S4:4x2]

<u>Rationale</u>: the single pixel value may not describe exhaustively the studied phenomenon (SO_2 emissions will likely extend beyond a single pixel)

<u>Observations</u>: peaks visible in the single pixel time series decrease rapidly with increasing window size; though not homogeneously during events

4) We computed **ratios between SO_2 observations at the crater and within the averaging windows** to better highlight peaks occurring at the volcano [S1/S2, S1/S3, S1/S4]

<u>Observations</u>: several peaks occur during intense events detected at the ground sensor networks, especially using the S1/S4 window

Ratio	Condition	No. of Occurrences	SO_2 Flux at ROC Station	
			≥70 t/d	<70 t/d
S1/S2	5 ≤ S1/S2 < 10	24	5	19
	S1/S2 ≥ 10	14	4	6
S1/S3	5 ≤ S1/S3 < 10	45	12	32
	S1/S3 ≥ 10	29	6	20
S1/S4	5 ≤ S1/S4 < 10	37	12	21
	S1/S4 ≥ 10	22	9	9

Total number of days when the ratios exceeded the selected thresholds (5, 10), compared with low (<70 t/d) and medium to very high (70 t/d) SO_2 flux measured at ROC station

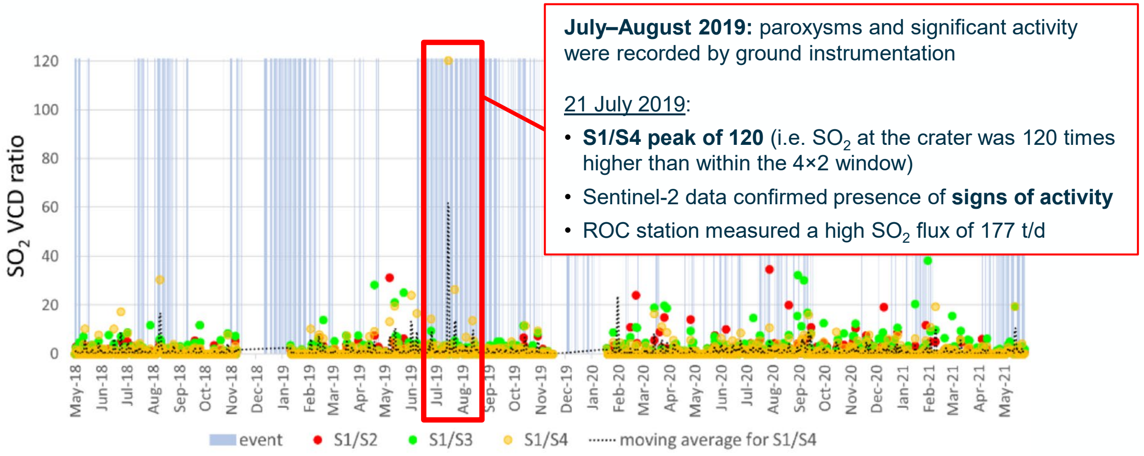
Integrated interpretation with Sentinel-2 imagery

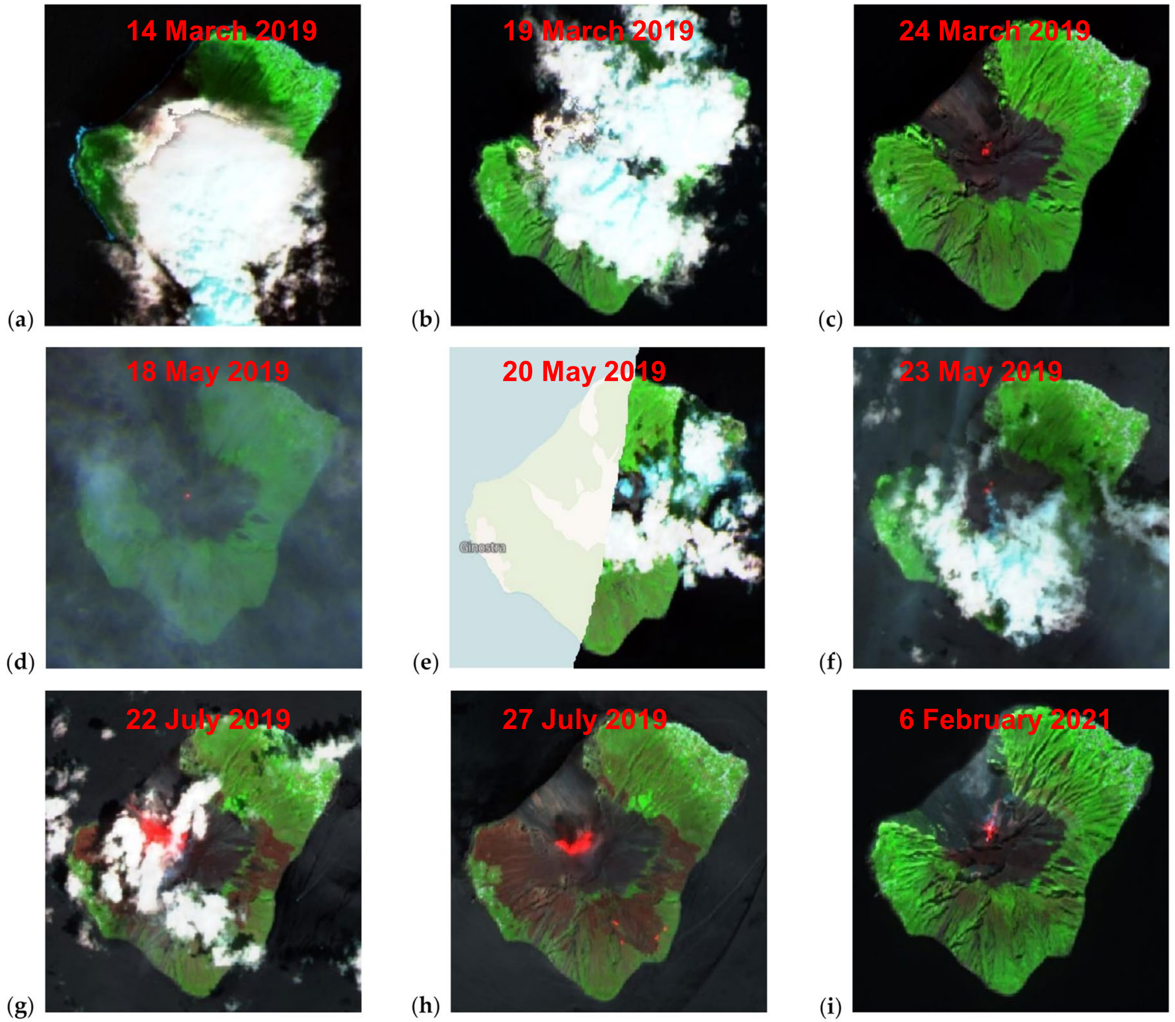
Contextual Sentinel-2 imagery as part of a more holistic set of Copernicus Programme observations (so-called “***virtual constellation***” concept) helps to refine the interpretation

A spatial analysis of VIS, NIR and SWIR bands provide **helpful information to contextualize and interpret SO_2 column density observations**

Despite the temporal shift in the ground and atmosphere scenario observed by Sentinel-5P and Sentinel-2, the latter provides high spatial and temporal resolution (i.e., 10 m VIS and NIR, every 5 days) that cannot be achieved with other satellites with open data policy

SO_2 VCD ratios between crater and averaging windows





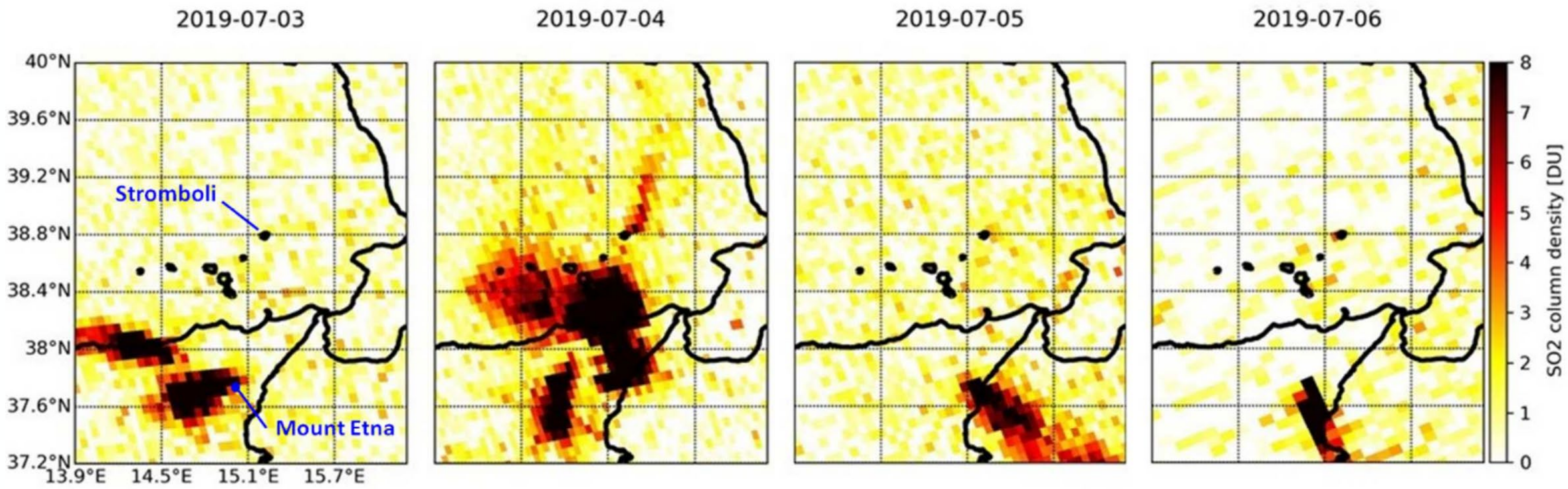
Sentinel-2 false color composites (R: band 12 SWIR; G: band 8A red edge; B: band 4 red)

Time lapses of the 2019–2021 eruptions

Based on the history of recent eruptions, 4 major events were selected and their evolution was tracked through daily SO_2 column time lapses

EVENT #1:

- A paroxysm occurred on 3 July 2019 (1 casualty!; see also previous slide), then activity intensified on 4 July (SO_2 flux of 80 t/d at the ROC station)
- Stromboli and Mt. Etna's plumes could be observed and distinguished, with ~1.9 DU (5.1 ×10[16] molecules/cm[2]) over Stromboli and more than 10 DU (26.9 ×10[16] molecules/cm[2]) just off the northern coastline of Sicily, clearly generated from Mt. Etna
- On 5-6 July, Mt. Etna's plume drifted towards the SE and SSE, away from Stromboli



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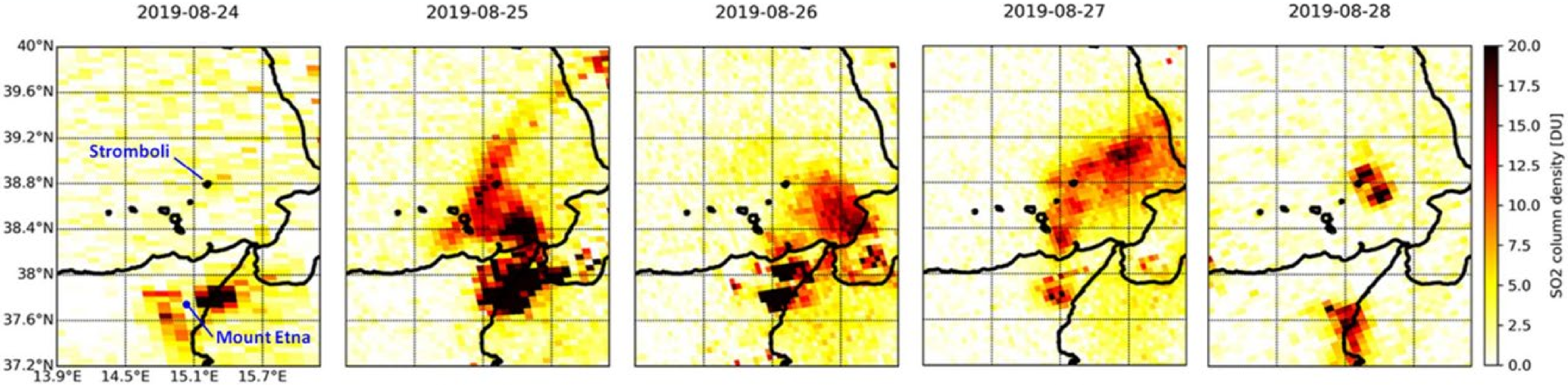
Time lapses of the 2019–2021 eruptions

Based on the history of recent eruptions, 4 major events were selected and their evolution was tracked through daily SO_2 column time lapses

EVENT #2:

- Mt. Etna eruption occurred contemporarily with that of Stromboli and, due to the winds, its plume covered Stromboli for many days (25-27 August)
- The two plumes cannot be easily separated from each other (clustered signals), and the observed SO_2 column values cannot be robustly associated with emissions from Stromboli only (many peaks in the time series at the crater actually could be mainly due to Mt. Etna's emissions)
- On 28 August at ~11:30 UTC the two signals did not overlap, enabling analysis of Stromboli's emissions without interference from Mt. Etna: a peak of ~3.0 DU (8.1 $\times 10^{16}$ molecules/cm^2) was detected at the crater, and 22.1 DU (59.5 $\times 10^{16}$ molecules/cm^2) a few kilometers to its northeast



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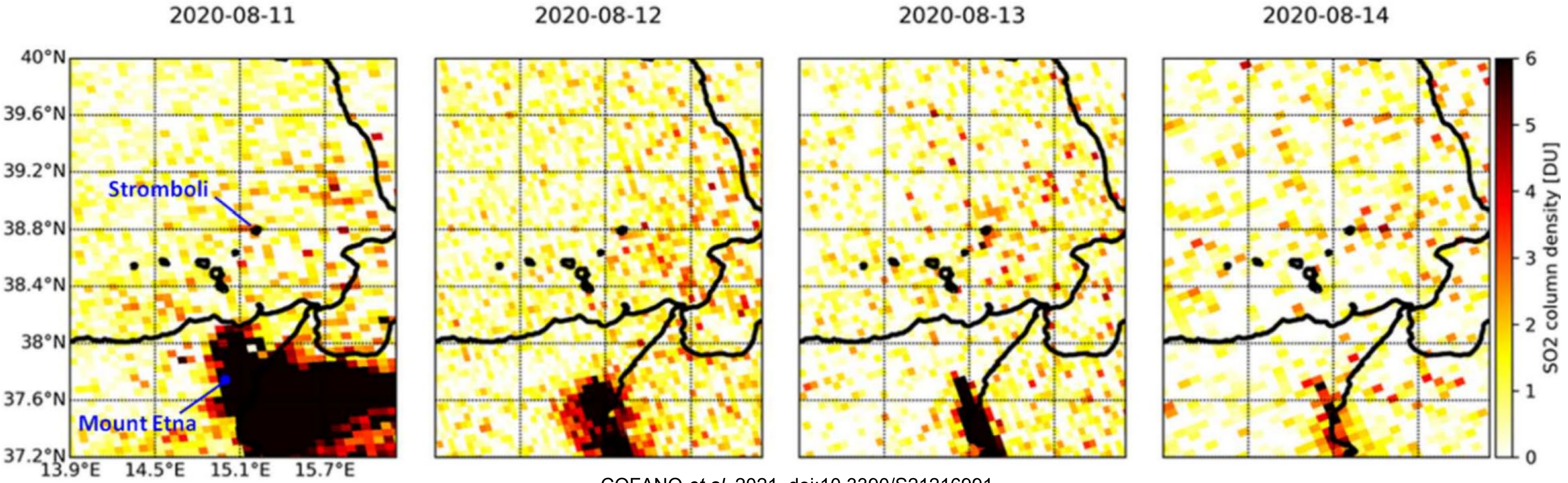
Time lapses of the 2019–2021 eruptions

Based on the history of recent eruptions, 4 major events were selected and their evolution was tracked through daily SO_2 column time lapses

EVENT #3:

- The time lapse shows a less distinguishable signal over Stromboli, with a column density of ~2.6 DU (7.1 × 10^{16} molecules/cm^2) on 13 August at the main crater, though without a clearly detectable plume
- In contrast, the plume of Mt. Etna extends for several square kilometers towards the east and south of its crater
- The SO_2 flux recorded at the ROC station was 59 t/d (low) on 11 August, and 112, 99 and 103 t/d (medium) on 12, 13 and 14 August, respectively



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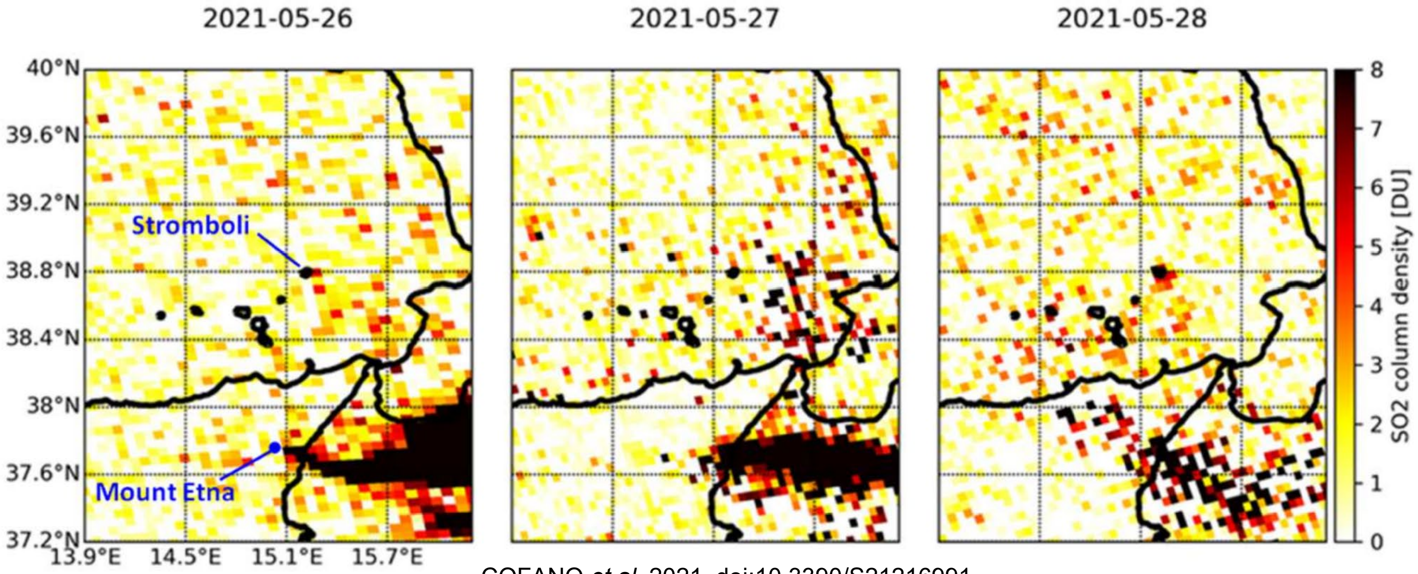
Time lapses of the 2019–2021 eruptions

Based on the history of recent eruptions, 4 major events were selected and their evolution was tracked through daily SO_2 column time lapses

EVENT #4:

- After months with low activity but keeping monitoring the volcano, a little bit more visible plume is found over Stromboli on 28 May 2021 with ~5.6 DU (15.2 ×10^{16} molecules/cm^2)
- The winds recorded at 10:00–13:00 UTC on that day at the WMO weather stations in Stromboli and Salina were relatively slow (~5 km/h)
- Stromboli and Mt. Etna's emission and plumes are distinguishable, with Mt. Etna's plume traveling towards E and not overlapping with Stromboli
- The SO_2 flux recorded at the ROC station was 123, 166 and 76 t/d (medium) on 26, 27 and 28 May, respectively



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Key conclusions

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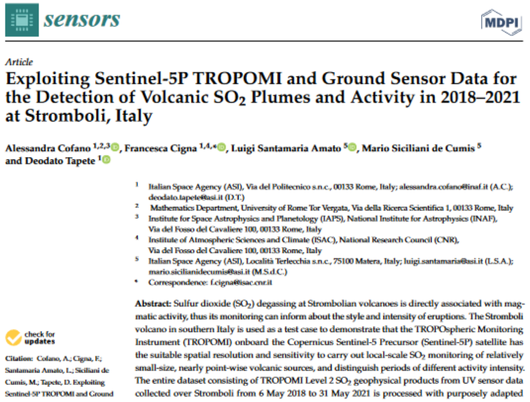
- The investigation of SO_2 emissions at Stromboli proves that Copernicus Sentinel-5P is a valuable space asset for monitoring volcanic activity of small-size Strombolian volcanoes, characterized by violent and explosive eruptions, as well as by persistent degassing
- The "virtual constellation" approach enables the synergistic use of TROPOMI's data and products together with other Copernicus Sentinel mission data, such as Sentinel-2 multispectral imagery, providing high-resolution information on the situation on the ground
- Our study helps to deepen the discussion on the practical/technical issues involved in handling and post-processing these geophysical data that are yet to become of common and standard use across the scientific community interested in volcanological applications
- The developed approach based on SO_2 VCD spatial averaging and ratioing for activity detection successfully identified degassing at Stromboli during periods of medium/high emissions, and could be exported to similar volcanic environments
- Clustered degassing from nearby natural and/or anthropogenic sources ('interference') might be carefully identified and accounted for, using other satellite data and/or ground-based information



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Article

Exploiting Sentinel-5P TROPOMI and Ground Sensor Data for the Detection of Volcanic SO_2 Plumes and Activity in 2018–2021 at Stromboli, Italy

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Citation: Cofano, A.; Cigna, F.; Santamaria Amato, L.; Siciliani de Cumis, M.; Tapete, D. Exploiting Sentinel-5P TROPOMI and Ground

Abstract: Sulfur dioxide (SO_2) degassing at Strombolian volcanoes is directly associated with magmatic activity, thus its monitoring can inform about the style and intensity of eruptions. The Stromboli volcano in southern Italy is used as a test case to demonstrate that the TROPOspheric Monitoring Instrument (TROPOMI) onboard the Copernicus Sentinel-5 Precursor (Sentinel-5P) satellite has the suitable spatial resolution and sensitivity to carry out local-scale SO_2 monitoring of relatively small-size, nearly point-wise volcanic sources, and distinguish periods of different activity intensity. The entire dataset consisting of TROPOMI Level 2 SO_2 geophysical products from UV sensor data collected over Stromboli from 6 May 2018 to 31 May 2021 is processed with purposely adapted

open access

COFANO A., CIGNA F., SANTAMARIA AMATO L., SICILIANI DE CUMIS, M., TAPETE, D. 2021. **Exploiting Sentinel-5P TROPOMI and Ground Sensor Data for the Detection of Volcanic SO_2 Plumes and Activity in 2018–2021 at Stromboli, Italy**. *Sensors*, 21(21), 6991. doi:10.3390/S21216991