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GLOBAL MONITORING OF VOLCANIC SO_2 DEGASSING USING SENTINEL-5 PRECURSOR TROPOMI

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ABSTRACT

We present here the TROPOMI SO_2 product, which is publicly available since April 2018. We describe the capabilities and limitations of the product for the monitoring of volcanic SO_2 degassing. With several examples, we illustrate the benefit of a small satellite pixel of 3.5 x 5.5 km². Owing to its improved detection limit, the data can be used to generate time series of SO_2 mass over number of volcanoes, with a large range of SO_2 emissions. We use Nyiragongo as a show case and correlate the SO_2 mass data with lava lake level estimates and local measurements of the seismicity. This paper also presents on-going developments to further improve the performance of the product for weak SO_2 loadings using a new algorithm, COBRA.

Index Terms—volcanic emissions, sulfur dioxide, monitoring, time series, satellite.

1. INTRODUCTION

Measurement of sulfur dioxide (SO_2) degassing is key for monitoring volcanic activity and, when used in conjunction with other types of measurements (e.g. of the seismicity, thermal emissions, ground deformation, etc.), for understanding volcanic processes. In this context, space-based measurements of SO_2 are particularly useful owing to their unlimited access to remote or poorly monitored volcanoes, or during large eruptions when ground-based infrastructures are typically overwhelmed. Over the last four decades, global satellites have been increasingly used to monitor and quantify volcanic SO_2 emissions, in particular from ultraviolet sensors [1]. Since April 2018, the TROPOspheric Monitoring Instrument (TROPOMI) provides open-access information on SO_2 worldwide with a daily revisiting time (see http://www.tropomi.eu/). Owing to its high spatial resolution of 3.5 x 5.5 km² (compared to previous UV sensors) and its good sensitivity in the lower troposphere, TROPOMI is uniquely positioned to detect weak volcanic SO_2 degassing emissions at the global scale (Figure 1). Moreover, recent studies [2,3] have shown that the analysis of high-resolution downwind patterns from TROPOMI bears important information on emission/eruption chronology at high temporal resolution, which were not available from any other satellite sensors.

In this paper, we present the TROPOMI SO_2 algorithm and illustrate the strengths of the product for monitoring volcanic SO_2 degassing via several examples. We give compact information on how to use the product and also highlight its main limitations. Finally, we present on-going efforts to improve the TROPOMI SO_2 algorithm with a new and highly sensitive scheme.

2. METHODOLOGY

The TROPOMI instrument [4] operates onboard the Sentinel-5 Precursor platform, the first Sentinel mission dedicated to the atmosphere. The satellite flies on a polar sun-synchronous orbit, crossing the equator at 13:30 local time. Owing to its large orbital swath of 2600 km, global coverage is achieved in nearly one day. TROPOMI has a resolution as good as 3.5 x 5.5 km². The instrument measures solar light backscattered from the atmosphere and reflected by the Earth in eight spectral bands covering the ultraviolet to shortwave infrared wavelengths. The operational retrieval of the SO_2 vertical column amount (i.e. total number of molecules per unit area) is performed in the ultraviolet (band 3) following a

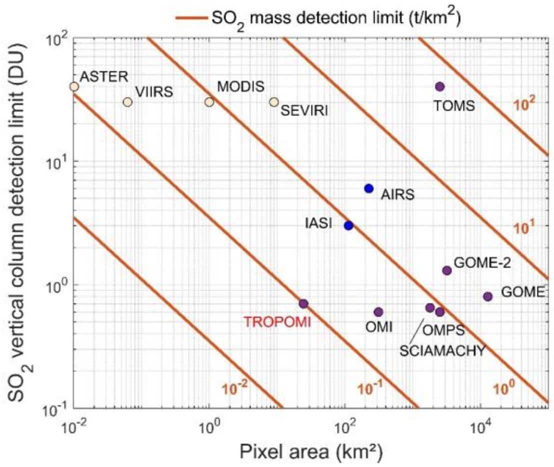

Figure 1. SO_2 vertical column detection limit (at 3-σ level) expressed in Dobson Unit (1DU=2.69×10^{16} molec/cm²) for a tropospheric plume at 3 km height, as a function of pixel size (in km²) for space nadir sensors with proven capability to detect SO_2. The orange lines are SO_2 mass detection limit iso-lines. Figure adapted from Theys et al. (2019).

Differential Optical Absorption Spectroscopy (DOAS) algorithm, described in details elsewhere [5]. In brief, the algorithm includes three main steps:

1. Wavelength calibration and spectral fitting: the spectral analysis of the measured intensities yields the SO_2 absorption strength, the so-called slant column density (i.e., the SO_2 concentration integrated along the light path). By default, the retrieval is done in the range 312-326 nm but to avoid possible saturation effects, two alternative windows (325-335 nm or 360-390 nm) are also considered for strong SO_2 signals.
2. Background correction: this step is needed to correct biases and across-track dependencies in the data.
3. Air Mass Factor (AMF) calculation: to convert slant columns into vertical columns, scaling factors (AMFs) are needed to account for the radiative transfer in the atmosphere. The AMF depends on the SO_2 vertical distribution, which is unknown. The AMF (and vertical column) is calculated for three hypothetical plume heights at 1, 7 and 15 km. For a certain volcanic event, it is up to the user to select the column with a representative height or to interpolate the three columns for a given plume height (estimated from independent sources).

For volcanic studies, the SO_2 mass is usually preferred over the SO_2 vertical column. Knowing the TROPOMI pixel spatial dimensions, the conversion to the SO_2 mass is straightforward and the total mass loading for a given day and geographical region can be obtained by summing the mass values of the pixels belonging to the volcanic plume. For this, it is handy to use the SO_2 detection flag (included in the files) to delineate the plume. Note however that at high-latitudes, the TROPOMI orbits are partly overlapping and, to avoid double counting, a common practice (in particular for large eruptions) is to grid the data and then estimate the total mass from the SO_2 mass value in each tagged grid cell. Finally, it should be emphasized that a more robust and geophysical quantity than the total SO_2 mass is provided by the SO_2 emission rate (in ton day^{-1} or kg s^{-1}). The later can be inferred from satellite SO_2 measurements using several techniques [1-3, 6] that usually combine satellite data with meteorological wind field information. This is however out of the scope of this paper.

3. RESULTS

The TROPOMI SO_2 product proves to be very useful for volcanic surveillance and near-real-time applications, such as the Support to Aviation Control Service (SACS; sacs.aeronomie.be) [7]. Figure 2 shows an example of an SO_2 plume injected at flight altitudes as observed by TROPOMI. The high-resolution mapping of SO_2 is a clear asset for simulating and forecasting the plume dispersion (and its many filaments) as the data essentially carries time- and height-resolved information on the source.

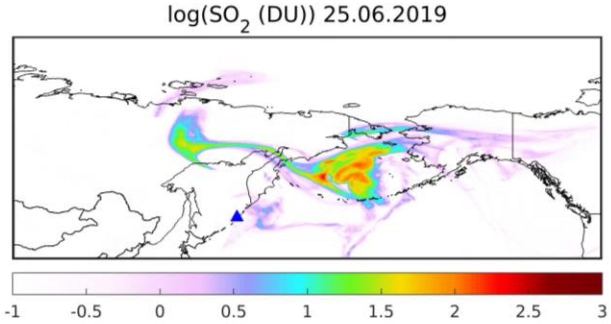

Figure 2. TROPOMI SO_2 vertical column (in logarithmic scale) on 25 June 2019, after the massive eruption of Raikoke (blue triangle). The total SO_2 mass is 1.27 Tg, assuming 15 km plume height.

We note however that errors in the retrieved SO_2 columns are rather frequent for fresh or high SO_2 plumes and are mostly due to the presence of large amounts of aerosols and limitations in the fitting windows transition [5].

Moving from large to much lower SO_2 emissions, Figure 3 shows an example of SO_2 column map over Chile-Argentina. Although the observed SO_2 is close to the noise level, an SO_2 plume originating from the Copahue volcano is clearly visible; the total SO_2 mass is of ~ 0.031 kt. Note that, compared to other UV sensors (like OMI), this particular SO_2 plume is only observed by TROPOMI and illustrates the improved detection limit of the instrument.

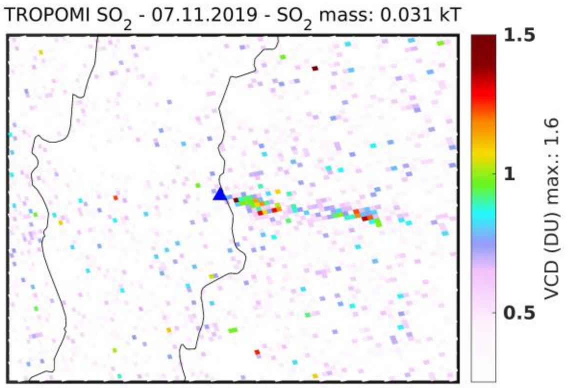

Figure 3. TROPOMI SO_2 vertical column on 07 November 2019. An SO_2 plume can discerned from the Copahue volcano (blue triangle). The total SO_2 mass is 0.031 kt, assuming 7 km plume height.

As an illustration of SO_2 mass time-series, Figure 4 shows the time evolution of the SO_2 emissions over Nyiragongo (Democratic Republic of Congo, DRC) measured by TROPOMI for one year. Nyiragongo is hosting a large lava lake, and its flank eruptions constitute a serious threat to the local populations (e.g., of the city of Goma). Therefore, active research and continuous monitoring of the activity of the volcano are very important. In Figure 4, the TROPOMI SO_2 mass estimates are confronted to data of the lava lake depth (obtained from SAR measurements [8]) and to the counting of deep seismic events [9]. As can be seen, the three largest SO_2 peaks in the TROPOMI data record are all directly connected to severe drops in the lava lake level, which are the consequence of deep magma intrusion events as deduced from the seismicity count below Nyiragongo (> 10 km depth b.s.l.). The increase of SO_2 emissions conveys here periods of sudden stronger lava lake spattering activity following these pressure drops, which are also inferred from the detection of high amplitude infrasound tremors (i.e., continuous acoustic explosion signals) [8]. A more detailed analysis of the lava lake dynamics is out of the scope of this paper but the results in Figure 4 highlight the great benefit of high quality satellite SO_2 measurements to study volcanic activity in connection with other satellite and ground-based measurements, in particular for regions such as DRC where local infrastructures are hard to maintain.

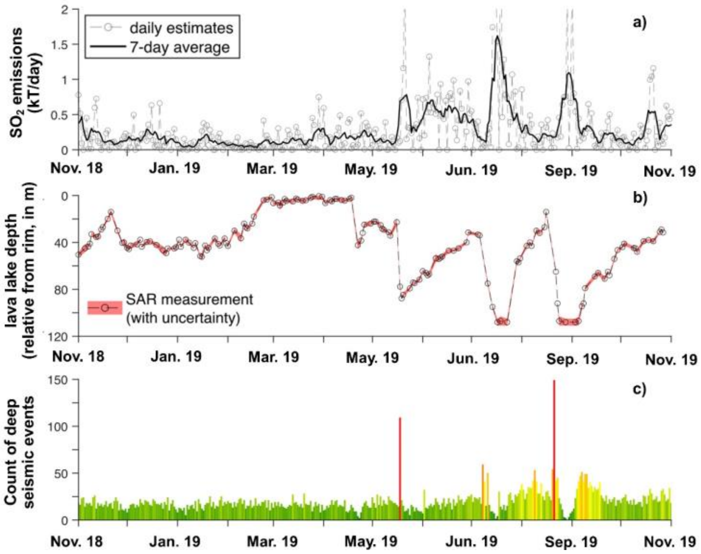

Figure 4. Time-series over Nyiragongo for Nov. 2018 - Nov. 2019 of (a) total daily SO_2 mass estimated with TROPOMI (assuming 4 km plume height), (b) lava lake depth from SAR measurements, (c) count of deep seismic events from seismic network (KivuSNet).

As a last example, we demonstrate here that TROPOMI also allows to study weaker volcanic SO_2 sources than those presented above. For this, it is common to average the data in time/space to reduce the data scatter. However, doing so is often not very successful because of local biases in the data. These are due to spectral misfits and are therefore not easy to correct. A new algorithm is under development that effectively suppresses the spectral interferences in the analysis. It is a Covariance-Based Retrieval Algorithm (COBRA) [10], which leads to very significant reductions of both the noise and biases in the data. As result, COBRA allows detecting very low volcanic emissions of SO_2 in long-term averaged data (as illustrated in Figure 5 over the Aleutian

Islands). This is a key step forward in terms of sensitivity, and will certainly enhance the use of TROPOMI for studying volcanic SO_2 emissions and trends.

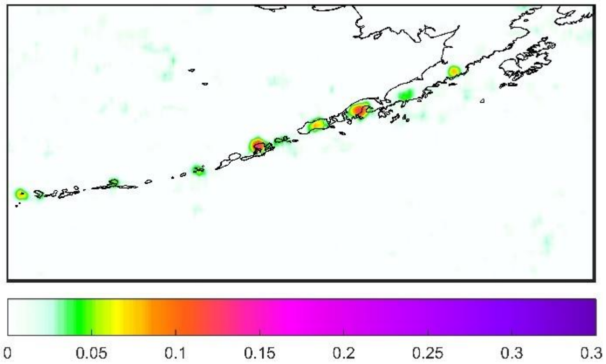

Figure 5. Detection of weak volcanic SO_2 sources in the Aleutian Islands (Alaska) by applying the TROPOMI COBRA schemes to two years of cloud-free observations (May 2018 - Avril 2020). The colors represent SO_2 column values in Dobson Units.

4. CONCLUDINGS REMARKS

We presented here the TROPOMI SO_2 data set and illustrated the capabilities and limitations of the product to monitor volcanic SO_2 degassing with several examples. The high spatial resolution of the instrument allows to infer detailed information on SO_2 emissions and to detect weaker sources than with any other satellite instrument. Taking advantage of the high measurement sensitivity, we illustrate with the case of Nyiragongo how the SO_2 mass estimated by TROPOMI can be related to volcanic processes and complements other geophysical measured quantities.

In the future, we expect further exploitation of the TROPOMI SO_2 data for volcanic surveillance and near-real-time applications. This will be particularly relevant with highly sensitive algorithms like the COBRA, briefly introduced here. An important step forward will be also to retrieve systematically the SO_2 flux from TROPOMI daily SO_2 measurements at many volcanoes worldwide.

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