Volcanic SO_2 by UV-TIR satellite retrievals: validation by using ground-based network at Mt. Etna

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Abstract

Mt. Etna volcano in Italy is one of the most active degassing volcanoes worldwide, emitting a mean of 1.7 Mt/year of Sulphur Dioxide (SO_2) in quiescent periods. In this work, SO_2 measurements retrieved by Moderate Resolution Imaging Spectroradiometer (MODIS), hyper-spectral Infrared Atmospheric Sounding Interferometer (IASI) and the second Global Ozone Monitoring Experiment (GOME-2) data are compared with the ground-based data from the FLux Automatic MEasurement monitoring network (FLAME). Among the eighteen lava fountain episodes occurring at Mt. Etna in 2011, the 10 April paroxysmal event has been selected as a case-study for the simultaneous observation of the SO_2 cloud by satellite and ground-based sensors. For each data-set two retrieval techniques were adopted and the measurements of SO_2 mass and flux with their respective uncertainty were obtained. With respect to the FLAME SO_2 mass of 4.5 Gg, MODIS, IASI and GOME-2 differ by about 10%, 15% and 30%, respectively. The SO_2 flux correlation coefficient between MODIS and FLAME is 0.84. All the retrievals within the respective errors are in agreement with the ground-based measurements supporting the validity of these space measurements.

I. INTRODUCTION

Monitoring active volcanoes is crucial for social, environmental and economic aspects, especially in a densely populated area such as at Mt. Etna in Italy. During the last 10 years, the surveillance of Mt. Etna ash cloud has seen a rapid growth due to technological advances that include the development of a warning system for paroxysmal events, real-time satellite observations and the forecasting of ash cloud movements [Andronico et al., 2009; Patane' et al., 2013].

The European Space Agency projects 'Study on an End-to-End system for volcanic ash plume monitoring and prediction' (SMASH and SACS2) are aimed at exploring the ability of operative polar-orbiting satellite instruments in the Ultraviolet to Thermal Infrared (UV-TIR) spectral range to retrieve quantitative measurement of volcanic SO_2 and ash cloud parameters. In particular, the MODIS on board NASA Terra and Aqua satellites, IASI on board EUMETSAT MetOp-A, and GOME-2 on board EUMETSAT MetOp-A and B satellites have been selected for generating SO_2 satellite products. Mt. Etna is the test site of the SMASH project while Eyjafjallajökull and Grímsvötn in Iceland are test sites of the SACS2 project [Koukouli et al., 2014]. In this work, part of the validation activities are presented. In particular, the MODIS, IASI and GOME-2 SO_2 retrievals are compared with the ground-based measurements obtained by the FLAME network of one of the short-lasting 2011 lava fountains episodes.

II. MT. ETNA 2011 LAVA FOUNTAINS

Mt. Etna is characterized by a constant degassing activity from its summit craters (3300 m a.s.l.) which produce volcanic plumes both from the summit and eruptive fractures that often open on the flanks of the volcano during eruptions.

Recently, Etna has frequently shown powerful explosive activity, including episodic paroxysms. Between 12 January and 15 November 2011, Etna produced eighteen lava fountains from the New-South East Crater. The eruptive episodes were characterized by paroxysmal phases, lasting from a quarter of an hour to three hours, preceded by mild strombolian activity and coupled with lava flows. Each paroxysm formed an eruption column ranging in height from 5 to 11 km a.s.l.. Although these eruptive episodes lasted just few hours, the volcanic clouds travelled thousand of km, mostly over the Mediterranean Sea and were tracked by polar orbiting instruments flying over the area [Behncke et al., 2014].

In order to select the events for validation, eruptive episodes need to be simultaneously observed from both satellite and ground-sensors. The most powerful and long-lasting lava fountains have been identified as measurable by space sensors. Since FLAME is based on UV spectroscopy, those episodes occurred during the night time have been excluded. Following these criteria, in the range of the eruptive sequence taking place in 2011, the 10 April event has been selected and presented hereafter as a case-study. The paroxysmal phase lasted about three hours, starting at 10.07 and ending at 12.56 GMT. The maximum ash cloud altitude estimated by ground video-cameras [Scollo et al., 2014] was over 9 km a.s.l. at 11.18 GMT.

III. GROUND SO_2 MEASUREMENTS

Since 2004, the daylight surveillance of Mt. Etna degassing is performed by the FLAME automated network that provides real-time and high-resolution SO_2 flux measurements [Salerno et al., 2009]. The network consists of 10 UV scanning spectrometers spaced ~7 km apart and installed at an altitude of ~900 m a.s.l. on the volcano flanks. During the daylight data are transmitted to the Istituto Nazionale di Geofisica e Vulcanologia (INGV), where reliable SO_2 flux is automatically computed, providing near instantaneous information on degassing rates and plume location. During the 10 April event, FLAME acquired data from 10.05 to 12.57 GMT with an SO_2 flux peak of ~15300 t/d at 10.53 GMT. At 12.24 GMT a second flux peak of ~11600 t/d was recorded suggesting a new impulse of fresh volatile-rich magma throughout the eruption.

IV. SPACE SO_2 RETRIEVALS

IASI SO_2 products were generated by two retrieval schemes, one developed by the Earth Observation Data Group at the University of Oxford (UNIOX) [Carboni et al., 2012] and one developed by the Atmospheric Spectroscopy group of the Université Libre de Bruxelles (ULB) [Clarisse et al., 2014]. The UNIOX scheme retrieves simultaneously the SO_2 plume height and the SO_2 column amount together with the retrieval errors. The ULB scheme retrieves the height prior to the column amount. The MODIS SO_2 products have been generated by INGV [Corradini et al., 2009] and by the Rutherford Appleton Laboratory (RAL) [Poulsen et al., 2011]. The INGV product is retrieved on a pixel by pixel weighted least squares fit procedure using measured and simulated radiances, including the ice/ash correction. The RAL product is based on the Optimal-estimation scheme. In particular, the scheme simultaneously retrieves ash and SO_2 contents once the cloud height is fixed a priori. The 8.7 µm band has been used for both products since it is sensitive to tropospheric SO_2 clouds. The technique to generate the GOME-2 SO_2 products was developed by the Deutsches Zentrum fur Luftund Raumfahrt (DLR) [Rix et al., 2012]. The inversion algorithm is based on a Differential Optical Absorption Spectroscopy technique, assuming three fixed cloud heights of 2.5 km, 6 km and 15 km a.g.l..

V. SPACE AND GROUND COMPARISON

During the 10 April paroxysm, MODIS Aqua detected the SO_2 plume at 12.30 GMT. Figures 1 a and b show INGV and RAL products: both detect two SO_2 plumes spreading toward SE directions from the summit of Mt. Etna. The INGV product shows a 12% greater area than the RAL product. In terms of the SO_2 column amount in the entire cloud area, the INGV product retrieves SO_2 values from 36% to 93 % higher with respect to RAL. The maximum of INGV SO_2 value is 300 +/- 100 DU while RAL retrieved 210 +/- 20 DU. The discrepancy is probably due to the assumptions adopted. The RAL a priori cloud height setting could affect the retrieval. The INGV retrieval considers the effect of ice particles detected in the cloud. The difference between the two retrieval techniques also derives from the number of pixels retrieved since the RAL product is one pixel for every two from INGV.

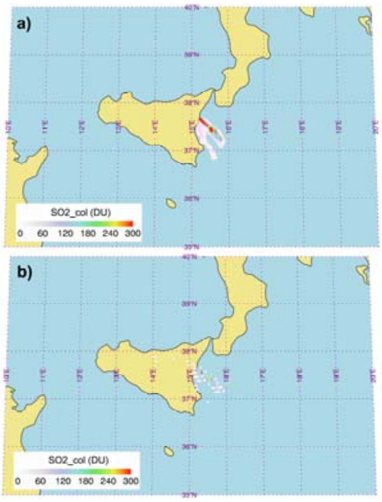

Figure 1: *MODIS 10 April 12.27 GMT SO_2 column amount: a) INGV and b) RAL.*

After the end of the paroxysm, IASI at 19.42 GMT captured the SO_2 cloud spreading south-east over the Mediterranean Sea (Figures 2 a and b).

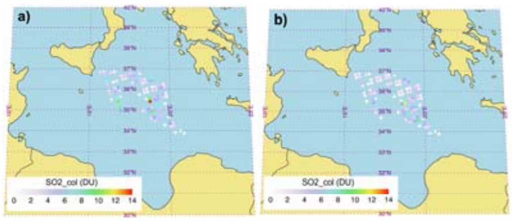

Figure 2: *IASI 10 April 19.43 GMT SO_2 column amount: a) UNIOX and b) ULB.*

The ULB product shows a 4% greater area than the UNIOX one. In terms of SO_2 content, UNIOX values are 17% greater with respect to the ULB product. The maximum SO_2 content of the ULB product is 12 DU compared to UNIOX SO_2 content of 14 +/- 2 DU. Also for IASI products, the differences between the two retrieval techniques are probably due to the retrieved cloud height: the higher the cloud height, the lower the SO_2 content. The day after the end of the lava fountain, both IASI and GOME-2 captured the SO_2 clouds over the eastern part of the Mediterranean Sea (Figure 3). The DLR product retrieves a maximum value of 2 DU. ULB product shows a 11% greater area than the UNIOX product. In terms of SO_2 content, UNIOX values are 23% greater with respect to ULB product. The maximum SO_2 content of the ULB product is 6 DU compared to UNIOX SO_2 content of 8 +/- 1 DU.

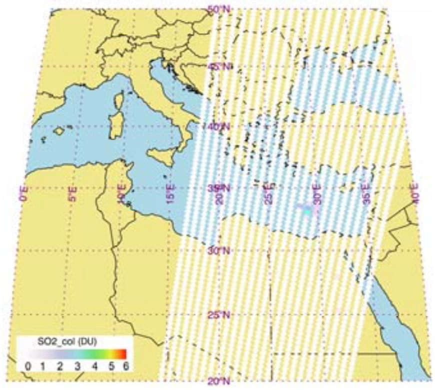

Figure 3: *GOME-2 11 April 07.44 GMT DLR SO_2 column amount.*

As aforementioned, the products have different SO_2 content and acquisition times depending essentially on sensor and satellite characteristics. In order to compare the SO_2 products with the ground-based data, the SO_2 Mass and the SO_2 Flux have been calculated.

SO_2 Mass. The SO_2 Mass emitted during the paroxysmal event has been obtained by reanalysis of the FLAME data. The total Mass of the entire paroxysm is (4.5 +1.3, -1) Gg. Since the Aqua satellite passed during the ongoing lava fountain, the SO_2 Mass from the FLAME network was calculated from the start time of the event to the time of the Aqua pass (12.27 GMT). For each of the satellite products, MODIS, IASI, and GOME-2, the SO_2 Mass has been calculated as a cumulative mass and averaged over the cloud area. Figure 4 shows the results of the comparison (dashed vertical lines indicate the event start and end). All the retrieved masses are the same order of magnitude of ground SO_2 Mass. The INGV, UNIOX, ULB and DLR masses are within the FLAME quoted uncertainties (grey area in Figure 4). On 10 April, the INGV mass concurs well with FLAME since the masses distance is about 10% of the quoted uncertainties. The UNIOX and ULB mass distances from FLAME are about 15%. On 11 April, the DLR differs from FLAME by about 30% and ULB differs by about 25%. Only RAL underestimates the SO_2 Mass by about 2 Gg. In addition, Figure 4 highlights the depletion of SO_2 in the cloud far away from the source (11 April GOME-2 and IASI).

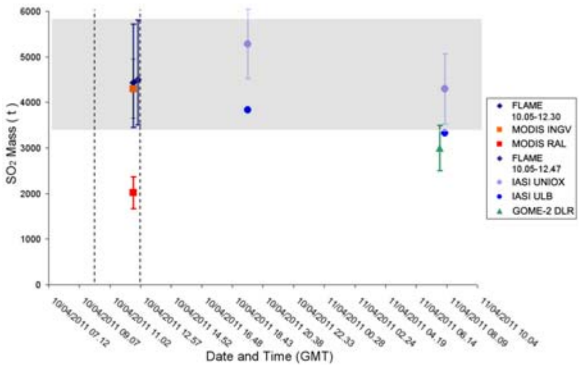

Figure 4: *SO_2 Mass comparison ground vs satellite measurements across Mt. Etna for the 10 April 2011 paroxysmal event.*

SO_2 Flux. The 10 April SO_2 Flux has been used to compare the MODIS INGV product with ground FLAME data, as the MODIS data was acquired during the paroxysm. The raw FLAME data were reprocessed in order to calculate the SO_2 flux assuming the same constant wind speed of 10 m/s and the same plume altitude assumed in the MODIS INGV product. This approach was adopted in order to compare the two fluxes. The MODIS SO_2 flux was computed by multiplying the integral of the columnar abundance along each plume transect orthogonal to the plume axis by the wind speed. From the computed SO_2 flux vs distance from the vent, the SO_2 flux time series was reconstructed, i.e. the SO_2 flux vs time of the emission. The correlation coefficient between MODIS and FLAME flux results in 0.84. A rather good agreement can be seen in Figure 5. The differences are in the grey zone, where land surface temperature and emissivity uncertainty leads to significant errors in MODIS SO_2 retrievals [Merucci et al., 2011].

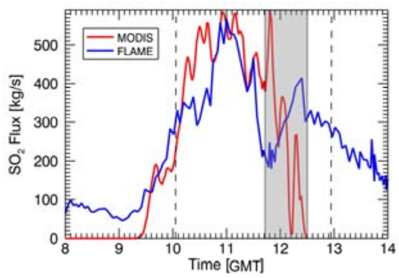

Figure 5: *SO_2 Flux comparison. The dashed vertical lines are the event start and end. The grey zone indicates where the MODIS retrieval is carried out on land.*

VI. CONCLUSIONS

A case-study was selected among the Mt. Etna 2011 lava fountain events in order to compare and validate the IASI, MODIS and GOME-2 products generated in the frame of the European Space Agency projects SMASH and SACS2. For the 10 April event, the IASI ULB and UNIOX, GOME-2 DRL and MODIS

INGV SO_2 mass values are rather well correlated with those of ground-based FLAME data, thus supporting the validity of such space measurements. Small differences in the retrieval algorithm of the cloud area and SO_2 amount have been evidenced for IASI ULB and UNIOX, GOME-2 DLR, while a greater difference was found between MODIS INGV and RAL. Results gathered in this work, though limited to a single case-study, suggest that satellite retrieval is a promising volcano monitoring tool for SO_2 volcanic cloud observation, providing day-night integration in the daylight ground-based SO_2 measurements records.

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