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PROXIMAL AND DISTAL MONITORING OF VOLCANIC ERUPTIONS FROM AN INTEGRATED APPROACH BASED ON MSG-SEVIRI OBSERVATIONS

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Abstract

Volcanic eruptions impact environment, climate and human health. In particular, the volcanic ash clouds represent a severe threat for aviation safety. The volcanic activity is monitored worldwide by using several satellite and ground-based instruments each of which has its advantages and drawbacks. To exploit the complementarity between space- and ground-based remote sensing systems, an integrated approach has been developed. The procedure is based on MSG-SEVIRI measurements and integrates in a novel manner the volcanic retrievals at the space–time scale of typical geostationary observations. The procedure is able to fully characterize the volcanic eruption from the source to the atmosphere and improve the volcanic cloud detection and retrievals (ash cloud mass loading, mean effective radius, aerosol optical depth and SO_2 mass loading). Volcanic eruption source parameters such as the eruptive column height, eruption start and duration, mass eruption rate, total erupted mass, and the total grain-size distribution can be also estimated and used to feed volcanic ash deposition and transport models.
These products can be used to evaluate in real time the impact of the volcanic eruptions on ground and in the atmosphere in order to support the civil protection and air-space traffic managers on their decision making processes.
As test cases the 49 lava fountains occurred at Etna volcano from 2011 to 2015 have been analyzed.

INTRODUCTION

Satellite and ground based remote sensing systems are used to monitor worldwide the volcanic activity. Because it doesn't exist a single remote sensing instrument able to provide a comprehensive description of a given phenomenon, an integrated approach is needed (Corradini et al., 2016; Marzano et al., 2018). An example is the retrieval of the volcanic cloud ash particles, generally carried out in the Thermal InfraRed (TIR) spectral range that allows the retrievals of particles in the range 0.5 - 15 μm. Particles smaller than 0.5 μm don't interact with the TIR wavelengths while particles larger than 15 μm produce the same Top Of Atmosphere (TOA) radiative effects, and therefore cannot be discriminated. To fully characterize of the ash particles emitted during an event, Visible (VIS) and MicroWave (MW) measurements are also needed.
In this work the proximal and distal monitoring of the volcanic activity is carried out by an integrated approach based on the measurements of the geostationary Spinning Enhanced Visible and Infrared Imager (SEVIRI) instrument aboard the EUMETSAT-Meteosat Second Generation (MSG) satellite. SEVIRI has 12 spectral channels from VIS to TIR with a spatial resolution of 3 km at sub-satellite point and a temporal resolution that ranges from 15 (Full Disk) to 5 minutes (Rapid Scan, only over Europe). The channels used in this work for the volcanic eruption monitoring are those centred at 3.9, 8.7, 11 and 12 μm (SEVIRI channels 4, 7, 9 and 10 respectively).
The integration is performed by considering the SEVIRI measurements as reference and exploiting the capabilities of satellites and ground based instruments data available. The developed procedure will allow the improvement of volcanic eruption source parameters retrievals (Corradini et al., 2018) (such as Volcanic Plume Top Height (VPTH), eruption start and duration, Mass Eruption rate (MER), total erupted mass (M_t), and the Total Grain-Size Distribution (TGSD)) and the volcanic cloud detection and retrievals (as the ash cloud mass loading (M_a), effective radius (R_e), aerosol optical depth (AOD) and SO_2 mass loading (M_s)). Moreover, the integrated approach allows the generation of new products such as the volcanic cloud ash concentration (C_a). Integrated products like the VPTH and the TGSD are used to feed volcanic ash deposition and transport models and to improve the forecast simulations (Poret et al., 2018).

As test cases, the developed integrated procedure has been applied to the 2011-2015 Etna lava fountains events (Behncke et al., 2014; Scollo et al., 2015). From 2011 to 2015, Mt. Etna volcano showed an intense explosive activity with 49 lava fountain events produced from the central craters, the most frequent of which were produced from the New South East Crater (NSEC), a new vent opened in 2010 at the base of the South East Crater (SEC). The main characteristic of these eruptions is that the most intense phase, commonly indicated as “paroxysmal” episodes, was generally very short (from minutes to hours). Moreover, these eruptions were characterized by three well defined phases including the rising of strombolian activity and lava flow emission, the formation of lava fountains with the production of abundant tephra fallout and the final decreasing of the explosive activity until the end of the eruption. All these phases have been revealed and characterized by remote sensing measurements.
The paper is organized as follows: at first the MSG-SEVIRI products, for both the proximal and distal monitoring of the volcanic eruption, are described. Then the integrated approach and the improved retrieval products are presented. Finally, the integrated products are used to feed the FALL3D dispersion and deposition model and the final conclusions are drawn.

THE MSG-SEVIRI PROXIMAL AND DISTAL VOLCANIC MONITORING PRODUCTS

In this Section the SEVIRI methodologies for the proximal and distal monitoring of the volcanic eruption are described and the products shown.

Eruption/Fountaining Start/End

The start, the end of the volcanic eruption and the fountaining phases are obtained by exploiting the MS2RWS (MeteoSat to Rapid Response Web Service) algorithm (Musacchio et al., 2011; Corradini et al., 2018). The procedure is based on the comparison between the radiance difference computed from the SEVIRI 3.9 μm radiances ($L_{3.9}$) of the pixel centred on craters and the mean value computed from the 5x5 pixels around it (DR), and the same difference computed considering reference values (DT). When DR > DT an eruption is occurring. **Figure 1** shows the DT, DR and $L_{3.9}$ trends during the 23 November 2013 event. The eruption start is defined by DR becoming greater than DT (at about 04:00 UTC) while the end corresponds to values of DR becoming lower than DT (at about 22:00 UTC). The coloured areas indicate the three phases characterizing all the 2011-2015 events: in red the rising of Strombolian activity with lava flow emission, in blue the formation of lava fountains with ash emission (the drop of DR is due to the ash absorption) and in green the decreasing of the explosive activity until the end of the eruption. The radiance drop between 13:30 and 16:00 UTC is due to a meteorological cloud passed over the area of interest.

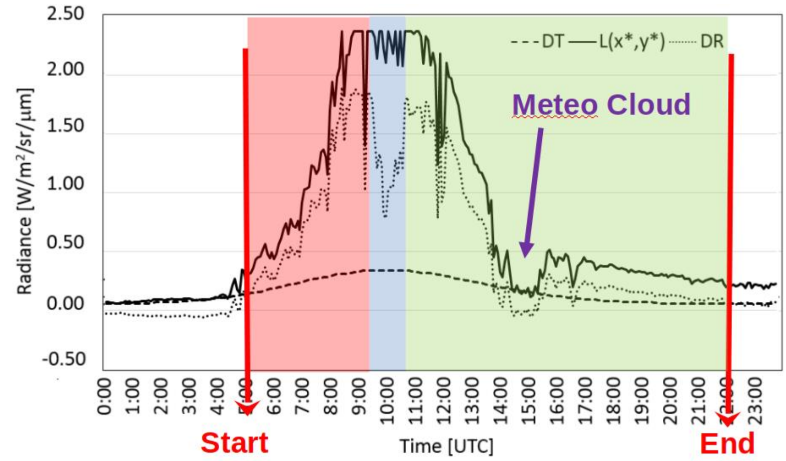


Figure 1: **DR (dotted line), DT (dashed line) and L(x*,y*) radiance (solid line) obtained from SEVIRI data collected during the 23 November 2013 Etna event. L(x*,y*) represent the radiance at 3.9 μm collected in the pixel centred on Etna vents. In the plot are indicated the start/end of the eruption and the three different phases characteristic of all the 2011-2015 events.**

Time Averaged Discharge Rate (TADR)

The Time Averaged Discharge Rate (TADR) is computed using AVHotRR routine developed by Lombardo (2015) to monitor volcanic activities in near-real time. AVHotRR allows automatic hot-spot detection and heat flux estimate. To convert the heat flux to TADR using the satellite thermal data, the well-established conversion of Harris et al. (1997) is applied. Since the SEVIRI pixel is about 9 square km, only a small fraction of lava generally occupies the pixel itself, making difficult the computation of the lava temperature (T_c), needed for the TADR retrievals (Corradini et al., 2018). In this case T_c is set by considering ad-hoc values (Harris et al., 2010) leading to TADR spanning over a wide range of values. ***Figure 2*** shows the TADR time series for all the 2015 events.

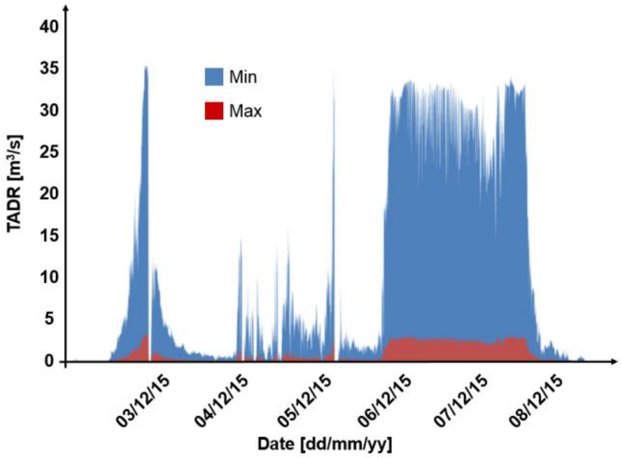


***Figure 2*: SEVIRI TADR. Blue and red values represent the maximum and minimum derived TADR respectively.**

Note the big uncertainty between the maximum and minimum TADR values.

Volcanic Plume Top Height

The Volcanic Plume Top Height (VPTH) is computed with a simple procedure based on the comparison between the 10.8 μm brightness temperature ($T_{b,11}$) of the “darkest pixels” of the volcanic cloud detected from the SEVIRI image, with the nearest atmospheric temperature profile collected in the area of interest at the same time of the satellite image acquisition (Prata and Grant, 2001; Corradini et al., 2010). ***Figure 3*** shows an example of the VCTH retrieval considering the SEVIRI image collected the 23 November 2013 at 11:00 UTC. The red line is the temperature profile derived from the WMO Trapani radiosounding in the same day of the SEVIRI acquisition at 12:00 UTC. The blue vertical solid and dotted lines are $T_{b,11}$ and the associated uncertainty, while the horizontal lines are the retrieved VCTH (solid line) and its related uncertainty (dotted lines).

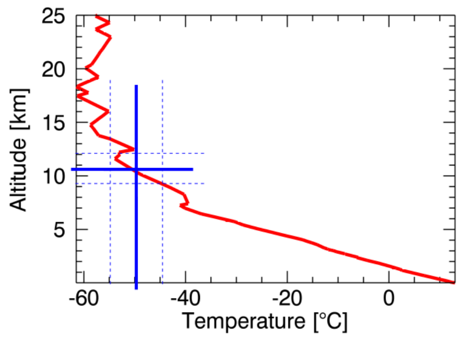


***Figure 3*: VCTH obtained from the analysis of the SEVIRI 23 November image collected at 11:00 UTC. In red the WMO Trapani radiosounding profile collected at 12:00 UTC.**

In Corradini et al., (2018) all the results for eruption/fountaining start/end, TADR and VPTH, for all the 49 2011-2015 lava fountains, can be found.

Volcanic Ash/Ice/SO_2 cloud Retrievals

The SEVIRI retrievals of volcanic ash/ice/SO_2 clouds is realized by using the Volcanic Plume Retrieval (VPR) approach (Pugnaghi et al., 2013; Guerrieri et al., 2015; Pugnaghi et al., 2016). The VPR is a real time procedure that approximates the relationship between the satellite TOA radiances with the transmittances using a set of parameters adapted for a specific area and volcanic cloud particle type (ash or ice). From the SEVIRI 8.7, 10.8 and 12 μm transmittances, SO_2 mass, ash and ice effective radius and optical depth are retrieved. Ash and ice masses are computed by means the Wen and Rose (1994) simplified formula. The only input required by the VPR procedure for the generation of all the volcanic cloud products, is VPTH. As Figure 4 shows, two clouds are formed, the first mainly composed by ash and the second mainly composed by ice and SO_2. These two clouds travel in different directions, the ash cloud towards north-east, while the ice/SO_2 cloud towards east.

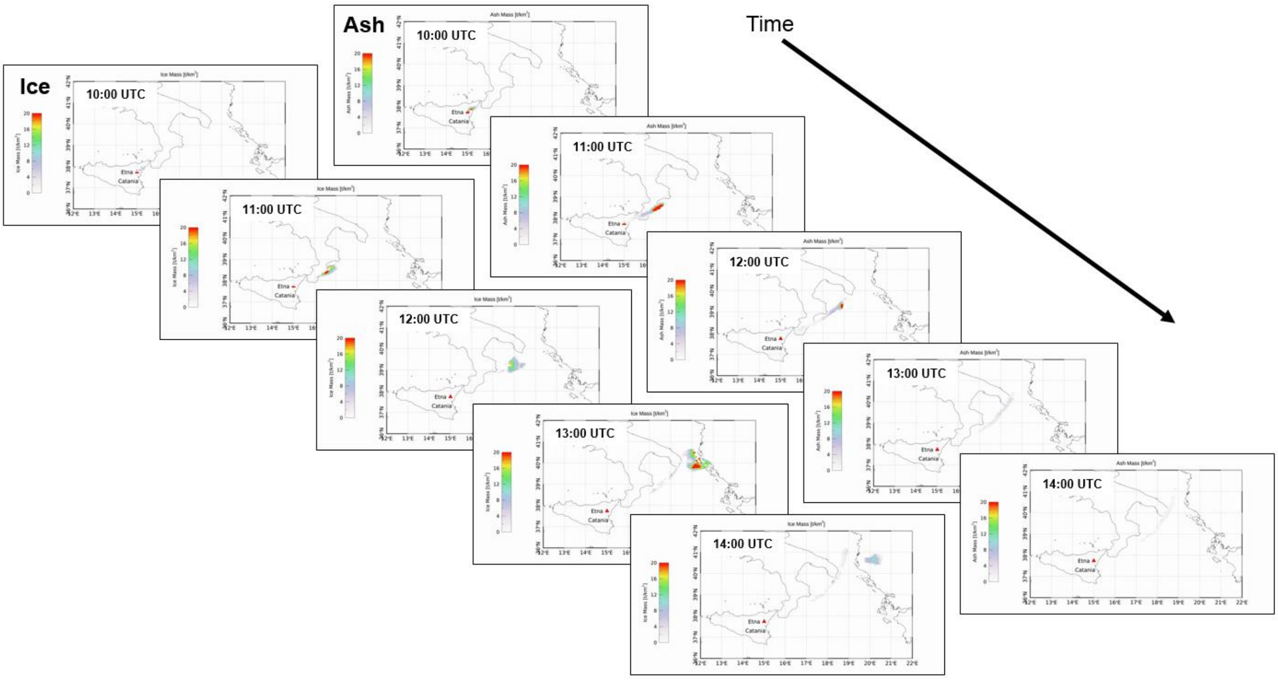


***Figure 4*: 23 November 2013 volcanic ash and ice cloud retrievals for different SEVIRI images.**

In ***Figure 5*** the time series of the volcanic ash, ice and SO_2 mass retrieved from all the images are displayed.

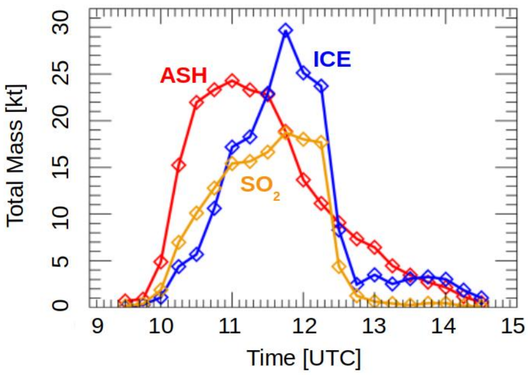


***Figure 5*: 23 November 2013 volcanic ash, ice and SO_2 mass time series**

INTEGRATION USING SATELLITE AND GROUND BASED DATA

Among SEVIRI, the 2011-2015 lava fountains have been also detected from LEO satellites and ground based instruments. In particular, the measurements of MODIS, aboard the NASA Terra/Aqua satellites, and the ground based radar X and VIS camera systems have been considered. ***Figure 6*** shows the main characteristics, the volcanic parameters retrieved and an example of the measurement carried out by the different instruments. The MODIS measurements can be used to retrieve the same parameters as SEVIRI with a higher spatial resolution, while the calibrated VIS camera can provide information on plume geometry as altitude and thickness. Also the Radar X measurements can be exploited to retrieve the volcanic cloud height, thickness, ash mass and grain size distribution. These latter measurements are particularly important because they complement the estimations obtained in the TIR spectral range from SEVIRI and MODIS. Ash particle effective radii retrieved in the TIR ranges from 0.5 to 15 μm, while in the MW (radar) also the particles greater than 20 μm can be detected and retrieved. Thus the integration of these measurements allows the whole characterization of the ash particles emitted, giving information on the total ash mass and the percentage of fine particles erupted. Moreover, the retrieval of the cloud thickness, is used to compute the volcanic ash concentration from the volcanic ash mass. This parameter is particularly important because it is used from the European Aviation Safety Agency (EASA) to classify the contaminated airspace (low contamination areas: 0.2 x 10^{-3} - 2 x 10^{-3} g/m^3; medium contamination areas: 2 x 10^{-3} - 4 x 10^{-3} g/m^3; high contamination areas: > 4 x 10^{-3}) in order to reduce the disruption of flights whilst still ensuring safe travels.

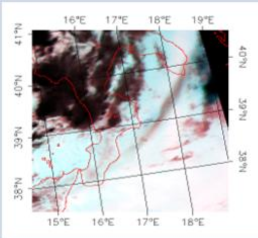
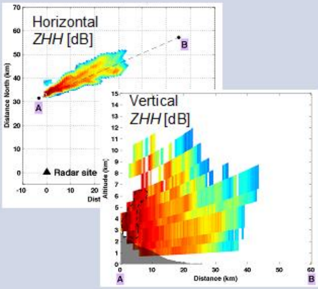
Instrument	*MODIS (aboard the NASA Terra and Aqua satellites)* 	*Ground based X Band Radar (Catania Airport)* 	*VIS Camera (Catania)*
Characteristic	➢ 36 bands from VIS to TIR ➢ Repetition cycle: 1/2 days ➢ TIR Spatial res.: 1 km^2	➢ ~3 cm wavelength ➢ Repetition cycle: 10 min ➢ 200 m x 1 deg resolution	➢ Images displayed 24h/7d ➢ 500 m resolution
Retrieval	➢ Ash/Ice/ mass, AOD, Re ➢ SO_2 mass	➢ Ash Mass [Re > 20 μm] ➢ Size Distribution ➢ Height, Thickness	➢ Height, Thickness
Measurement	MODIS-Aqua 12:45 UTC 	10:10 UTC 	09:30 UTC 

Figure 6: **Satellite and ground based instruments description, used for the integration with SEVIRI.**

The integrated approach developed (Corradini et al., 2016) is called Multi-platform volcanic Ash Cloud Estimation (MACE) and is based on GEO-SEVIRI measurements. The basic idea is to continuously improve both the volcanic ash retrievals and the source characterization by exploiting the complementarity between measurements and integrating all the LEO and ground-based data. ***Figure 7*** shows the MACE flow diagram: every 15 minutes the SEVIRI retrievals are integrated by using all other the available remote sensing data.

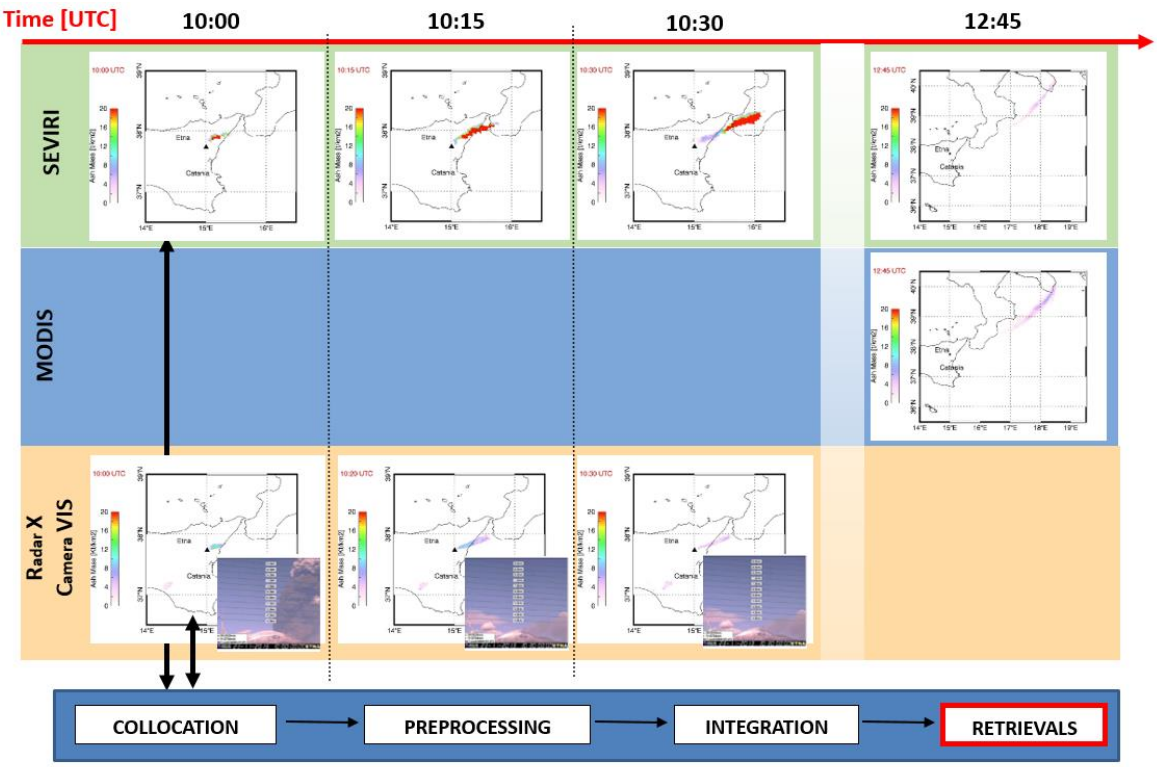


Figure 7: **MACE Temporal flow diagram**

At first, all the measurements are collocated at the same latitude-longitude projection and then interpolated in the same SEVIRI grid. The collocation allows the possibility to exploit the parallax between measurements and to compute the volcanic cloud altitude. From two collocated volcanic cloud images (SEVIRI-MODIS or SEVIRI-

RadarX), a cross correlation is realized in the pre-processing phase. The estimation of the displacement vector (length and direction) allows the computation of the volcanic cloud altitude which is particularly important because it is needed as input to the VPR procedure, for the retrievals of the volcanic ash/ice and SO_2.
Figure 8 shows the MACE integrated results for the 23 November 2013 for both proximal and distal monitoring: the combined use of the different remote sensing systems allows the estimation of the time series of VPTH (left panel), the determination of the altitudes of the two volcanic clouds composed by ash and ice/SO_2 (centre-left panel), the time series of the total ash mass emitted divided by fine and coarse particles (centre-right panel) and the ash concentration map (right panel). The different altitudes of the volcanic ash and ice/SO_2 clouds justify their different directions.

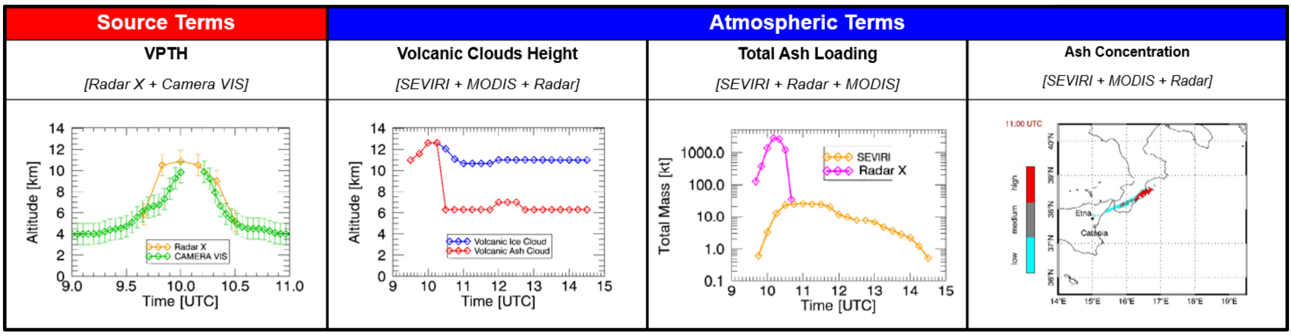


***Figure 8*: MACE integrated products for the 23 November 2013 event.**

Figure 9 shows the improvement of the SEVIRI TADR for the December 2015 events, obtained by exploiting the Advanced Very-High-Resolution Radiometer (AVHRR) data. The AVHRR is a multispectral instrument on board the NOAA satellites with 6 channels from VIS to TIR and a spatial resolution of 1.1 km. In particular, the channel 3B, centred at 3.8 μm, is used for the TADR computation. The AVHRR has a higher spatial resolution than SEVIRI, allowing to improve the computation of the temperature Tc and to significantly reduce the SEVIRI TADR uncertainties.

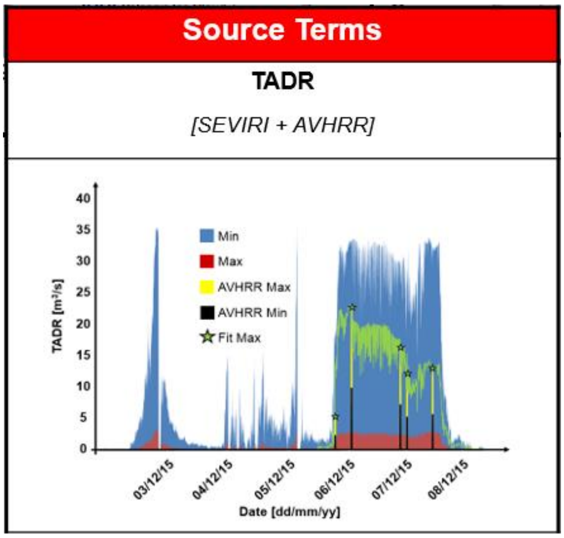


***Figure 9*: TADR integrated product for the December 2015 events, obtained by considering the AVHRR satellite measurements.**

In Figure 9 are shown the maximum (yellow bars) and minimum (black bars) TADR derived from 5 AVHRR images collected from 6 to 8 December 2015. The green line indicates the maximum SEVIRI derived TADR, rescaled using the maximum TADR derived from AVHRR. Minimum values are not shown in the graph for clarity. Figure also shows that, the SEVIRI TADR uncertainties are significantly reduced (Corradini et al., 2018) by using only few AVHRR images.

ASSIMILATION ON DISPERSION AND DEPOSITION MODELS

The integrated products can be used to feed dispersion and deposition models in order to improve the ground deposit and volcanic cloud forecasts (Poret et al., 2018) obtained by the FALL3D model (Costa et al., 2006; Folch et al., 2009). ***Figure 10*** shows the standard inputs generally used in the models and the integrated inputs obtained from the data integration. The constant VPTH for the whole lava fountain duration, is replaced with the VPTH time series retrieved from the VIS camera and Radar X. The TGSD derived only from field measurements is replaced with the TGSD obtained by considering also the ash particles retrieved from Radar X and SEVIRI (i.e. finer particles have been added to the field TGSD).

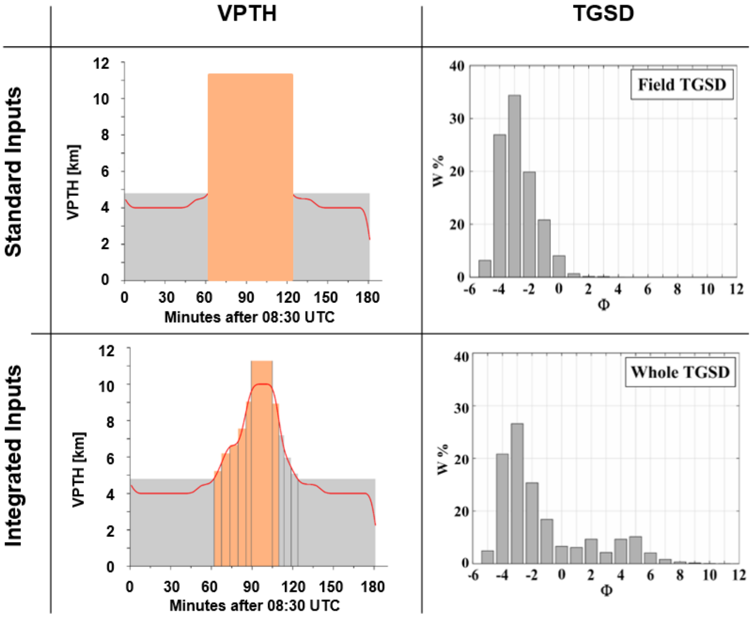


***Figure 10*: FALL3D standard and integrated inputs.**

The simulation results obtained from the standard inputs are shown in ***Figure 11***: the shape of the two volcanic clouds is obtained and the ash deposit reached Puglia as found by ground measurements.

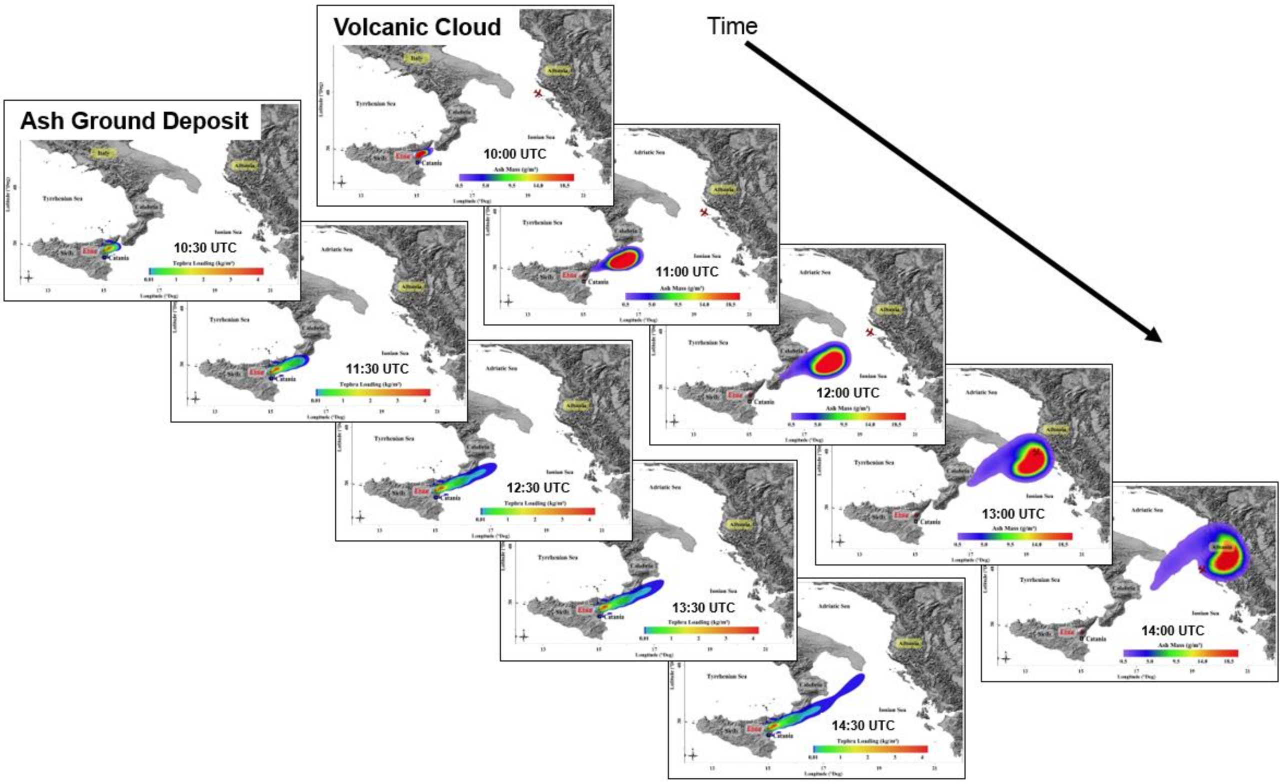


***Figure 11*: FALL3D volcanic cloud and ground deposit modelling.**

CONCLUSIONS

In this work both proximal and distal monitoring of the volcanic activity is realized by developing an integrated approach that exploits the complementarity between different remote sensing measurements. The integration approach, named Multi-platform volcanic Ash Cloud Estimation (MACE), is performed by considering the

SEVIRI measurements as reference and exploiting the capabilities of all the other satellites and ground-based instruments data available. As test cases, the 49 lava fountain events, occurred at Etna between 2011 and 2015, have been considered.
As results show, the integrated procedure improves the volcanic eruption source parameters retrievals as the volcanic plume top height (then the mass eruption rate), the total erupted mass (giving also the percentage of fine ash from the total ash erupted) and the total grain-size distribution. The spatial collocation between the different remote sensing products realized in MACE, allows the determination of the volcanic cloud altitude needed for the retrievals of the volcanic cloud parameters as ash effective radius, aerosol optical depth and mass and SO_2 mass. Moreover, the integrated approach allows the generation of new products such as the volcanic cloud ash concentration, an important parameter used from the European Aviation Safety Agency to classify the contaminated airspace in order to reduce the disruption of flights whilst still ensuring safe travels. The volcanic plume top height and the total grain-size distribution integrated products have been finally used as input for the volcanic ash deposition and transport model FALL3D to improve the forecast simulations.
All the products described are available in real time and can be used to support the civil protection and air-space traffic managers on their decision making processes.

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