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Key Points:

- We took the time-varying discharge rate of explosive eruptions into account
- We model volcanic ash dispersal including the variation of input parameters
- We compare model and lidar-derived concentration and the uncertainty

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Volcanic ash concentration during the 12 August 2011 Etna eruption

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Abstract Mount Etna, in Italy, is one of the most active volcanoes in the world and an ideal laboratory to improve volcano ash monitoring and forecasting. During the volcanic episode on 12 August 2011, an eruption column rose up to several kilometers above sea level (asl), and the volcanic plume dispersed to the southeast. From the video-surveillance system, we were able to estimate variations in the column height (peak value of 9.5 ± 0.5 km above sea level) with time. We derived the time-varying discharge rate (peak value of $60 \text{ m}^3 \text{ s}^{-1}$) and determined the ash concentration using a volcanic ash dispersal model. The modeled ash concentration was compared with lidar measurements using different particle effective radius, and differences are within the error bars. Volcanic ash concentrations range from 0.5 to $35.5 \times 10^{-3} \text{ g m}^{-3}$. The comparison highlights that to improve volcanic ash forecasting during volcanic crises it is necessary to take into account the time-varying discharge rate of explosive eruptions.

1. Introduction

On the morning of 12 August 2011, the New South East Crater of Etna volcano (Italy) produced the tenth event of the 2011–2012 eruptive sequence. The eruption generated a powerful lava fountain, during the most intense phase, forming a several kilometer high eruption column (Figure 1a). Volcanic ash dispersal simulations, running daily at the Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo (INGV-OE), forecasted that the volcanic plume dispersal was to the southeast. Nevertheless, the features of the 12 August 2011 lava fountain event differed from those used in running the daily simulations [Scollo *et al.*, 2009]; and consequently, the modeled ash concentration may have been different from the actual ash. The 12 August 2011 event features were similar to that of lava fountains occurring in the year 2000 [Alparone *et al.*, 2007] while they differed from the 1998 [Scollo *et al.*, 2008], the 2001 [Scollo *et al.*, 2007], and 2002–2003 eruptions [Andronico *et al.*, 2008]. For those events, the eruption source parameters needed by volcanic ash dispersal models were accurately identified and are used as reference scenarios to run the daily simulations [Scollo *et al.*, 2009]. The use of eruptive scenarios is applied worldwide and is an effort to improve the accuracy of simulations in the early hours of an eruption [Mastin *et al.*, 2009], though the limitations of this are well known owing to the unpredictability of the future eruptions [Folch, 2012]. In this paper, we first make an attempt to take the evolution with time into account.

The frequent explosive activity has prompted the INGV-OE to improve its volcanic plume monitoring and forecasting system through the introduction of new remote sensing techniques that can collect data in near real time [Scollo *et al.*, 2012; Pisani *et al.*, 2012; Scollo *et al.*, 2014]. The biggest limitation in forecasting the volcanic plume dispersal is the lack of rapidly available direct observations in the initial stage and during an eruption that may be used to run numerical simulations [Bonadonna *et al.*, 2012]. The INGV-OE monitors the activity of Sicilian volcanoes through a video-surveillance system made up of visible and thermal cameras that at the time of the eruption were located in Catania (ECV), Milo (EMV), Nicolosi (ENV and ENT), SchiENA dell'Asino (ESV), and La Montagnola (EMOV and EMOT) (Figure 1b). Recently, Scollo *et al.* [2014] proposed a method to estimate the column height by combining wind forecasts and images of the ECV camera. In this paper, we demonstrate that the combination of ground-based video surveillance and lidar systems may substantially improve the measurement of volcanic particles and that leads toward a reliable quantification of volcanic ash concentration in the atmosphere. We use the observations of the column height (CH) obtained

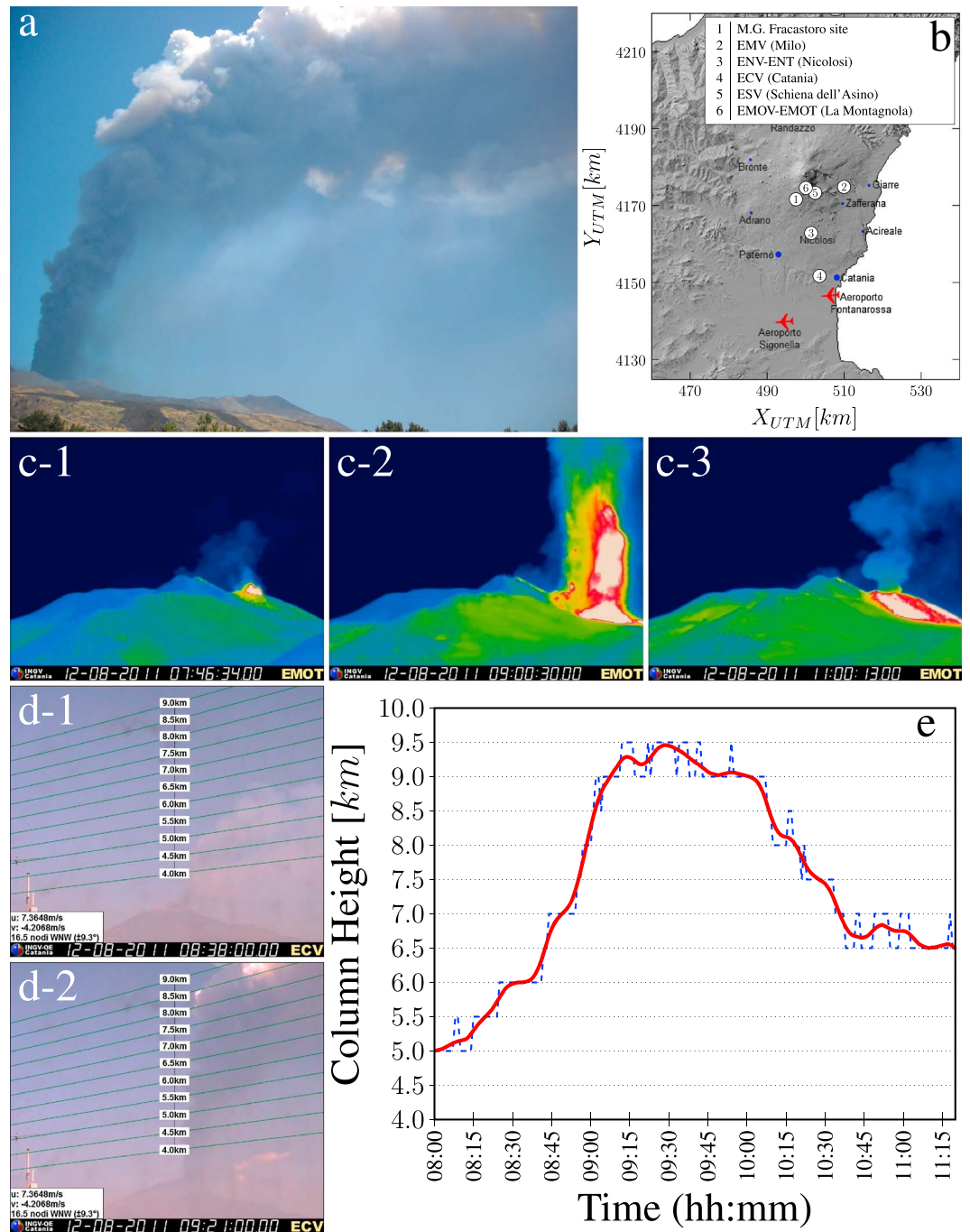


Figure 1. (a) Photo of the 12 August 2011 eruption column taken by S.Scollo at the M.G. Fracastoro site of the Istituto Nazionale di Astrofisica; (b) map including all the locations reported in the paper. Eruptive activity seen by EMOT of (c-1) Phase 1; (c-2) Phase 2; (c-3) Phase 3; images of the ECV camera used to estimate the column height at (d-1) 08:38 UTC and (d-2) 09:21 UTC using the method proposed by Scollo *et al.* [2014]; and (e) variation of the column height with 5 min time steps (blue line) and variation of the column height with 5 min time steps using a low-pass filter (red line) obtained by the analysis of the ECV images.

by the video-surveillance images to evaluate in near real time the time variations of mass eruption rate (MER) and include both eruption source parameters in the modeling. Volcanic ash concentrations obtained by computer simulations are then compared with those estimated by a scanning lidar system [Scollo *et al.*, 2012]. For the first time at Etna, we have been able to quantify the volcanic ash concentrations in the atmosphere.

This study may help quantify the impact that Etna's lava fountains have on aviation safety to prevent the flights in the areas of high contamination ($>4 \times 10^{-3} \text{ g/m}^3$) in compliance with the International Civil Aviation Organization directives [International Civil Aviation Organization (ICAO), 2010].

2. The 12 August 2011 Paroxysm

The 12 August 2011 lava fountain event was preceded by an increase in the amplitude of volcanic tremor several hours before the onset of the paroxysmal phase [D'Agostino *et al.*, 2013]. Sporadic ash emissions came early the strombolian activity that intensified from about 05:30 to 07:30 UTC, while at the same time there was a gradual increase in volcanic tremor [D'Agostino *et al.*, 2013]. After 07:30 UTC, strombolian explosions produced dark ash puffs (Figure 1c-1, Phase 1), and a lava flow was emitted at the base of the cone at 07:50 UTC toward the Valle del Bove [Behncke *et al.*, 2014]. The activity increased in frequency and intensity progressing from violent strombolian explosions to a sustained lava fountain at about 08:30 UTC [D'Agostino *et al.*, 2013]. The eruption column rose high above the vent between 08:45 and 10:00 UTC (Figure 1c-2, Phase 2), and after 10:30 UTC, the activity decreased and completely ceased around 11:00 UTC (Figure 1c-3, Phase 3). After the end of the activity, the lava flow reached a length of 2.9 km, the volume was estimated between 1.29×10^6 and $2.20 \times 10^6 \text{ m}^3$ with a mean effusion rate of $323 \text{ m}^3/\text{s}$ [Behncke *et al.*, 2014]. The volcanic plume dispersed toward the southeast; tephra fell on the towns of Zafferana and Milo, and as far as the Ionian coast covering a wide area between Giarre and Acireale towns (Figure 1b).

3. Column Height Estimation by the ECV Camera

We applied the method of Scollo *et al.* [2014] to the 12 August 2011 event for evaluating the column height with a resolution of $\pm 500 \text{ m}$. The method consisted of estimating (i) the intrinsic parameters of the ECV camera, (ii) the full camera model to locate any image point in the space of the camera field of view, (iii) the geometry of the plume considering the vertical plane passing through the volcanic vent and parallel to the mean wind direction. The eruptive activity began to intensify at 08:30 UTC, and the column rose to $6.0 \pm 0.5 \text{ km asl}$, remaining constant up to about 08:40 UTC (Figure 1d-1) and then increased by about 1 km in only 5 min (08:45 UTC). The ECV camera retrieved the value of $9.0 \pm 0.5 \text{ km asl}$ between 09:00 and 10:00 UTC (Figure 1d-2). Figure 1e shows the variation of the column height (asl) with a time step of 5 min. At the beginning of the lava fountain, the column rose up to $5.0 \pm 0.5 \text{ km asl}$. The activity slowly decreased, and the column descended to 8.0 km altitude asl at 10:22 UTC, and then to $6.5 \pm 0.5 \text{ km asl}$ at 10:30 UTC, maintaining this height until the end of the eruptive activity.

4. Lidar Measurements

Volcanic ash measurements were carried out by the Volcanic Ash Monitoring by Polarization lidar system installed at the M.G. Fracastoro site (14.97E, 37.69 N) of the Istituto Nazionale di Astrofisica, 7 km away from Etna's summit craters. The backscatter coefficient profile was obtained by the lidar measurements using the Klett-Fernald algorithm [Fernald, 1984; Klett, 1985]. The lidar ratio (LR) inside the plume was assumed of about 36 sr, as described in Pisani *et al.* [2012]. The calibrated particle linear depolarization values in the plume were obtained from the ratio of the power measured in the parallel and perpendicular polarized channels. The angular misalignment of the receiving optics was also taken into account [Pisani *et al.*, 2012]. The contribution of background aerosol load was considered negligible, less than $\sim 10^{-7} \text{ sr}^{-1} \text{ m}^{-1}$ in the Mediterranean region in clear-sky conditions [Sicard *et al.*, 2011].

Lidar measurements were carried out from 08:59 to 11:56 UTC. Figure 2a-1 shows the aerosol backscattering coefficient values (β_{aer}) and the aerosol depolarization profiles (δ_{aer}) obtained from the measurements performed by pointing the laser beam toward the plume for 10 min (09:01–09:11 UTC) and when the eruption column (at 09:01 UTC) reached the height of $9 \pm 0.5 \text{ km}$ (Figure 2a-2). Lidar profiles showed two layers with different properties. The first layer (Layer 1), between 5.5 and 6.1 km from the lidar station along the laser beam, was characterized by lower β_{aer} ($\sim 0.15 \times 10^{-5} \text{ m}^{-1} \text{ sr}^{-1}$) and $\delta_{\text{aer}} \sim 5\%$. The second layer (Layer 2) located between 6.2 and 6.8 km was characterized by peak values of β_{aer} around $1 \times 10^{-4} \text{ m}^{-1} \text{ sr}^{-1}$ and δ_{aer} of about 20%, suggesting that volcanic ash was mainly contained in this layer. Figure 2b shows the map of β_{aer} measured starting from 10:22 to 10:28 UTC with an integration step of 60 s. In order to probe the volcanic plume, the scanning was performed by changing the lidar elevation between 20° and 59° in elevation with a

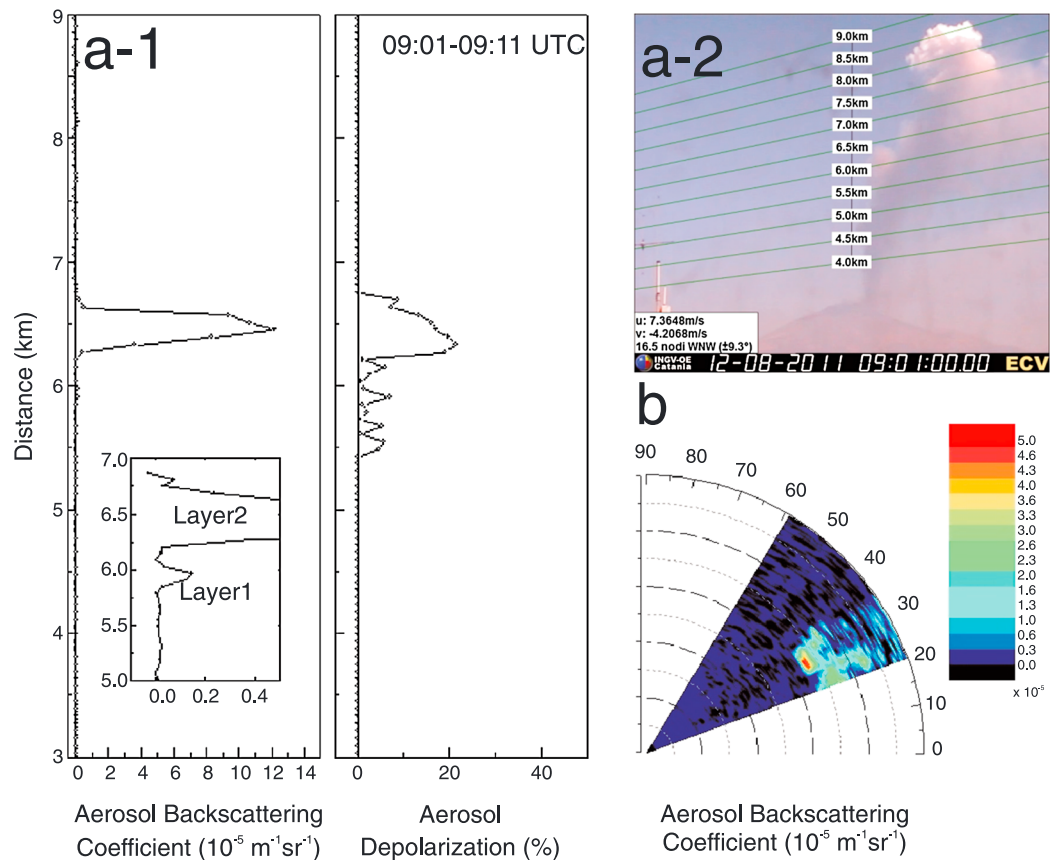


Figure 2. (a-1) Aerosol backscattering and aerosol depolarization profiles measured at Serra la Nave station on 12 August 2011. Data started at 09:01 UTC and were acquired for 10 min with an integration time of 60 s; (a-2) ECV image showing the column height between 8.5 and 9 km asl at 09:01 UTC; and (b) particle backscattering ($\text{m}^{-1} \text{ sr}^{-1}$) from 10:22 to 10:28 UTC of the scanning measurements, with elevations between 20° and 59° and azimuth of 36.7° . Integration time was 60 s.

fixed azimuth of 36.7° . The volcanic particles were located between 6.5 km and 8.0 km from the lidar station along the laser beam, in agreement with a column height of about 7.5 km asl estimated by the video-surveillance images recorded between 10:22 and 10:28 UTC. Inside the plume, the mean value of β_{aer} was about $2 \times 10^{-5} \text{ m}^{-1} \text{ sr}^{-1}$ and reached the maximum value of about $5 \times 10^{-5} \text{ m}^{-1} \text{ sr}^{-1}$ at 30.4° , about 6.5 km from the lidar station along the laser beam.

5. Ash Concentration Estimation

Volcanic ash concentration in the air was simulated using the Lagrangian numerical model named PUFF [Searcy *et al.*, 1998; Tanaka and Yamamoto, 2002; Webley *et al.*, 2008]. We made some changes to the original code and applied a statistical procedure to evaluate ash concentrations in the atmosphere [Scollo *et al.*, 2011]. For the first time at Etna, we took the time variations in the eruptive activity into account. In the simulations, we included the variations of both column heights (CH) retrieved by the ECV camera (Figure 1d) and the mass eruption rates (MER) obtained by applying the relationship $\text{CH} = 0.3035 \times \text{MER}^{0.241}$ [Mastin *et al.*, 2009]. The total grain size distribution was assumed constant for all the runs and equal to values reported in Andronico *et al.* [2014] that are suitable for lava fountain events occurring between 2011 and 2012. This distribution peaked at -3ϕ ($\phi = -\log_2(d)$ where d is the particle diameter in mm), has a median value of -1.4ϕ , and was extrapolated using an exponential fit to take into account the contribution of particles up to 8ϕ ($\sim 4 \mu\text{m}$). The percentage of the fine particles ($<30 \mu\text{m}$) was $\sim 1.5\%$, consistent with values reported from Gurrieri *et al.* [2015]. We ran 28 different simulations that all began at 08:30 UTC and ended at 11:30 UTC. Each simulation had only one 5 min eruption that occurred between 08:30 and 10:45 UTC and was constrained with the MER from the ECV camera. The simulations were then summed together to encompass the total eruption duration

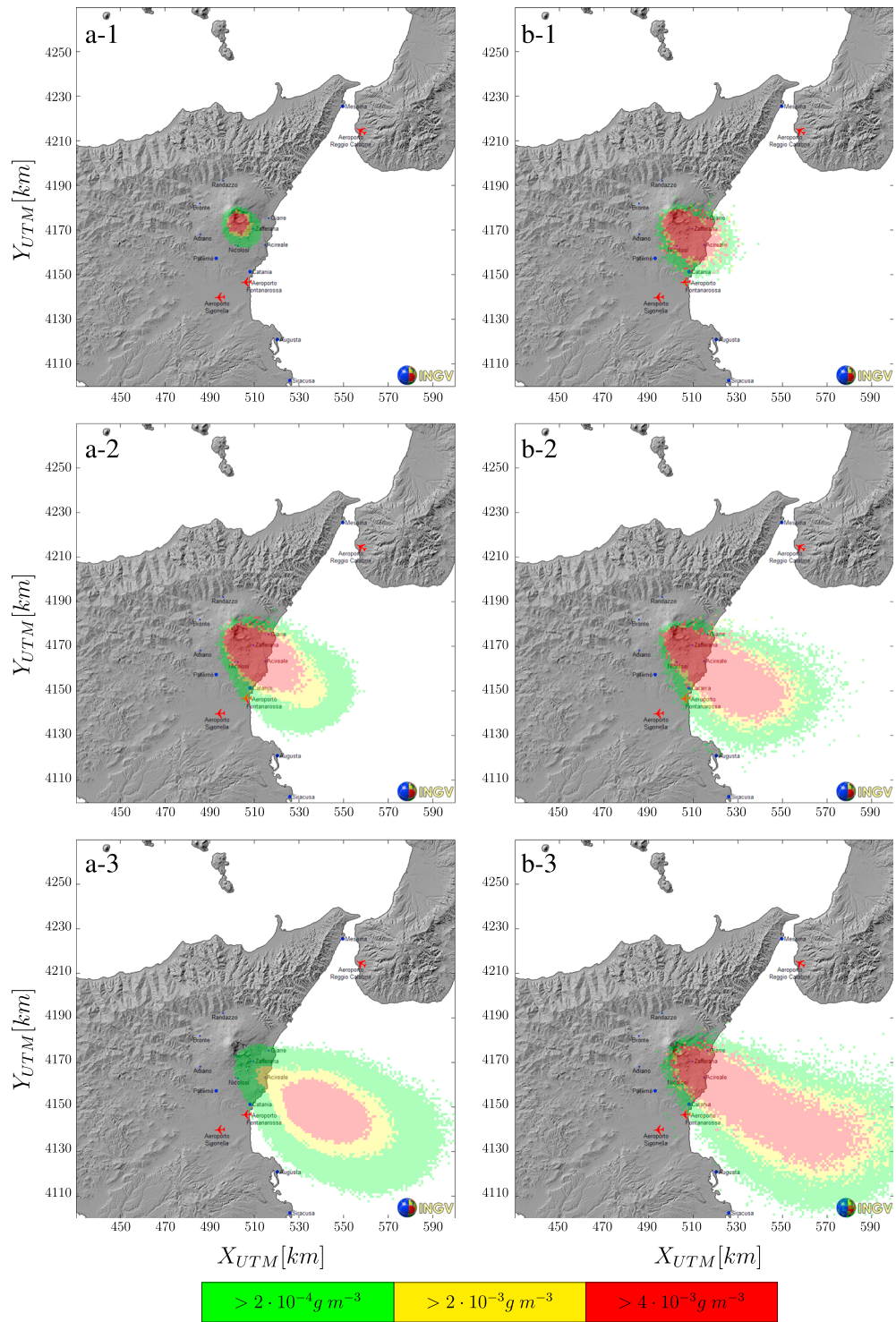


Figure 3. Volcanic ash concentration map plotted at 7 km asl and computed by the PUFF model using a variable mass eruption rate at (a-1) 09:00 UTC, (a-2) 10:00 UTC, and (a-3) 11:00 UTC and a constant mass eruption rate at (b-1) 09:00 UTC, (b-2) 10:00 UTC, and (b-3) 11:00 UTC.

and the mass ash concentration in the atmosphere at any specific time. The end time of each simulation was set to 11:30 UTC. The results of each simulation were summed to estimate the mass ash concentration in the air at any specific time. In agreement with *Scollo et al.* [2011], the number of particles used in the simulations was 5 millions while the time step was set to 1 min. For example, the PUFF result at 10:05 UTC is

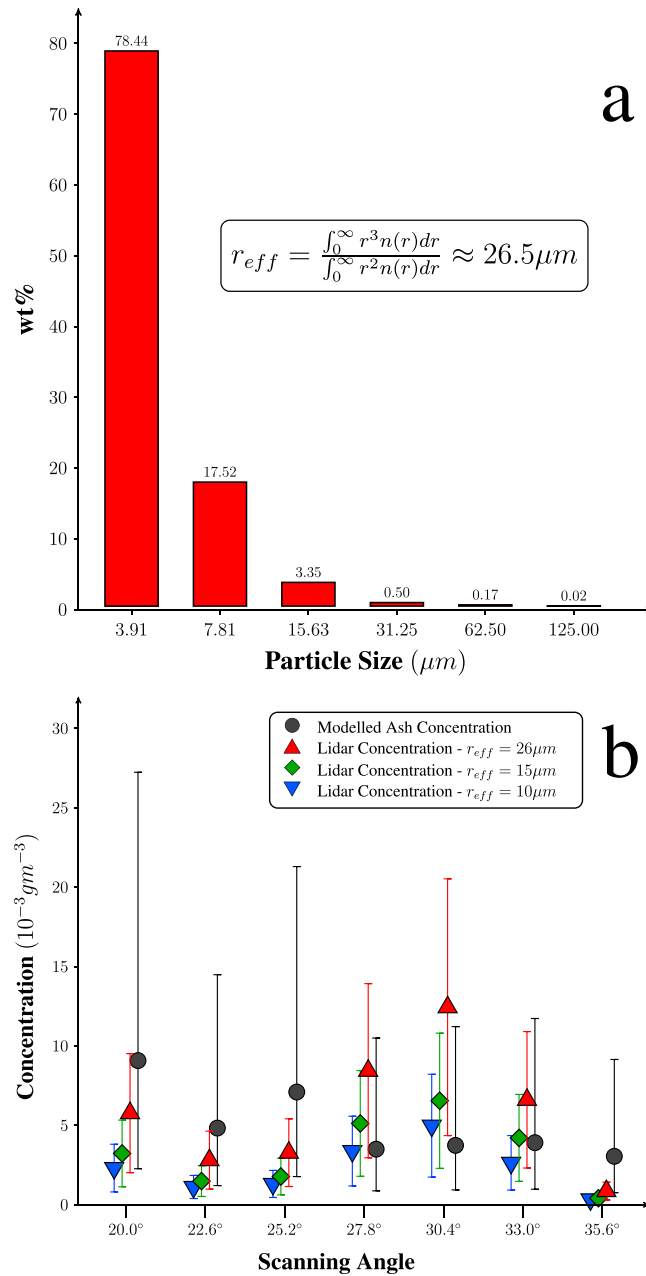


Figure 4. (a) Particle size distribution obtained from the PUFF model inside the region investigated by lidar, and (b) comparisons between volcanic ash concentration computed and measured by lidar using three different effective radius (r_{eff}). Error bar for the modeled ash concentration is related to the MER error; error bar for the lidar ash concentration is set to 55%.

given by the sum of all the simulations between 08:30 and 10:00 UTC. Meteorological data were provided by the Italian Air Force Meteorological Office and Italian National Department of Civil Protection, and covered the entire area of Sicily [Scollo *et al.*, 2009]. The PUFF results at 09:00, 10:00, and 11:00 UTC for 7 km asl using a variable MER (Figures 3a-1–Figure 3a-3) and a constant MER (Figure 3b-1–Figure 3b-3) are shown for comparison. The ash concentration thresholds are 2×10^{-4} , 2×10^{-3} , and $4 \times 10^{-3} \text{ g m}^{-3}$ [ICAO, 2010]. Simulations clearly show that Etna’s eastern and south eastern flanks are affected by volcanic ash dispersal and that after 11:00 UTC the ash concentration was less than $2 \times 10^{-4} \text{ g m}^{-3}$. The simulations using a constant MER computed a wider area affected by ash at the beginning and end of the explosive activity. If the volcanic cloud had expanded above the eastern flight zone, it would have been dangerous for aviation safety. We compared the results of simulations with lidar measurements retrieved between 10:22 and 10:28 UTC. Ash concentrations from lidar measurements were obtained following the approach described in Pisani *et al.* [2012] and Scollo *et al.* [2012]. First, we evaluated the ash-related backscatter coefficient β_a following the method proposed by Tesche *et al.* [2009]:

$$\beta_a = \beta_{aer} \frac{(\delta_{aer} - \delta_{na})(1 + \delta_a)}{(\delta_a - \delta_{na})(1 + \delta_{aer})}$$

where β_{aer} and δ_{aer} values are the aerosol backscatter and depolarization coefficients obtained by lidar measurements, δ_{na} and δ_a are the depolarization ratio coefficients of the depolarizing ash and of the weakly depolarizing nonash aerosol, and are set to 0.01 and 0.5. Then we obtained the volcanic ash concentration c by

$$c = k \times LR \times \rho \times \beta_a$$

where k is the ash conversion factor which is a function of the effective particle radius r_{eff} ($k = 2/3 r_{eff}$). LR is the mean value of the estimated lidar ratio, ρ is the density of volcanic ash fixed to 2450 kg/m^3 , and β_a is the ash-related backscatter coefficient [Pisani *et al.*, 2012]. We evaluate the lidar concentrations using three different r_{eff} . The r_{eff} was set to $10 \mu\text{m}$ and $15 \mu\text{m}$ consistent with values reported by Guerrieri *et al.*

[2015] and set to 26 μm obtained by simulations computed by PUFF in the same area investigated by lidar (Figure 4a):

$$r_{\text{eff}} = \frac{\int_0^{\infty} r^3 n(r) dr}{\int_0^{\infty} r^2 n(r) dr}$$

where r is the particle radius and $n(r)$ is the number density per unit radius [Stevenson *et al.*, 2015].

Figure 4b shows the comparisons between the modeled ash concentration and the lidar-derived concentration for three different particle sizes (10, 15, and 25 μm). Following Pisani *et al.* [2012], error on ash mass concentration obtained by lidar is evaluated from statistical uncertainties of βa , LR, and ρ resulting in the order of 55%. Error in ash mass concentration estimated by modeling is related to the fact that the equation of Mastin *et al.* [2009] has an inherent accuracy and uncertainty to a factor of 2. Results show that the modeled ash concentrations are comparable with those obtained by lidar for three different particle sizes. Lidar measurements reflected the pulsating nature of the lava fountain activity (high-frequency magma jet forming a fairly constant eruption column) that was not simulated in the modeling because the MER was set constant inside 5 min.

6. Discussion

The estimation of eruption source parameters during an eruption is a challenge that volcano observatories and scientific communities should pursue and make available to the Volcanic Ash Advisory Centre (VAAC). The main uncertainties of eruption source parameters are due to variations of eruption column height, mass eruption rate, total grain size distribution, and meteorological data [Scollo *et al.*, 2008; Mastin *et al.*, 2009; Webley *et al.*, 2009; Bonadonna *et al.*, 2012]. The combination of volcanological observations and modeling has allowed, for the first time at Etna volcano, to evaluate the volcanic ash concentration in the atmosphere and the degree of its uncertainty during the 12 August 2011 event.

The methodology presented in this work highlights different aspects. The measurement of eruption column height, in fine weather conditions, may be obtained by an inexpensive video-surveillance system [Scollo *et al.*, 2014]. Therefore, MER may be obtained by the well-known formulation that links it to the column heights. It should be noted that, for this eruption, the effect of the wind was negligible since the eruption occurred in low-wind condition (<10 m/s), and the values of MER are similar to those obtained by models taking account of the wind speed [e.g., Degruyter and Bonadonna, 2013]. Furthermore, the MER values show reasonable agreement with those obtained applying the 1-D dimensional model that takes into account effects of water, condensation, and ice formation on plume dynamics, as well as the effect of water added to the plume at the vent [Mastin, 2007].

During volcanic eruptions, column height is important to evaluate the area that may be affected by volcanic ash and forecast the region that should be avoided by aircraft [e.g., Tupper *et al.*, 2009]. The value of column height usually represents the maximum height reached by the plume. It is noteworthy that, depending on the eruption style, the column may reach the maximum height for a period less than the total eruption duration. In our study, the maximum column height (≥ 9 km) was between 09:02 and 10:07 UTC, about half of the duration of the explosive phase. Consequently, the area affected by ash ($>2 \times 10^4$ g m $^{-3}$) computed by models that consider a constant column height for the entire eruptive period will be greater than the area that should be if the variable column height is taken into account. The use of time-varying mass eruption rate estimated by ground-based observations coupled with a volcanic ash dispersal model could reduce this gap and will have a closer match to the eruption's mass ash concentration obtained considering a constant eruption rate.

Our analysis could help the VAAC to improve forecasts and hazard assessments during an eruption, but the following three important steps are still needed: (i) improvement of the column height retrieval, while images may be generated during the eruption in less than 5 min, the values of column height are checked by the operator who may take up to an hour for the analysis; (ii) rapid communication among volcano observatories and VAACs, meaning enhanced collaboration among different agencies; and (iii) improvement of computing time. We take about 3 h to run our simulations, but the use of clusters could considerably reduce the time needed to run thousands of simulations. Furthermore, some researchers have suggested using probabilistic approaches [Madankan *et al.*, 2014] which could replace the existing deterministic approaches

[e.g., Witham et al., 2007; Webley et al., 2008]. We believe that probabilistic approaches may be applied during an impending eruption when data on eruption source parameters are not available. Greater efforts should nonetheless be made to render observations accessible to inverse approaches [Stohl et al., 2011] so that decision makers have reliable information during volcanic emergencies.

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