

3D VOLCANIC AEROSOL DISPERSAL: A COMPARISON BETWEEN MISR DATA AND NUMERICAL SIMULATIONS

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Abstract

The three dimensional reconstruction of volcanic plumes is a central goal to enhance our understanding on dispersal processes. In this paper, we use data from the Multi-angle Imaging SpectroRadiometer (MISR) on board NASA's Terra spacecraft combined with a stereo matching retrieval procedure. We show the potential of MISR in capturing important features of volcanic plumes like column height, optical depth, type and shape of the finest particles of two highly explosive eruptions occurring on Mt. Etna in 2001 and 2002. This work tests how tephra dispersal models reconstruct the 3D shape of volcanic clouds. We compare MISR data with FALL3D, an Eulerian model for the transport and deposition of volcanic ash and aerosols coupled with the Weather Research and Forecasting (WRF) mesoscale meteorological model. Agreement between simulations and MISR data is good regarding both events, although it could be improved by increasing the accuracy of the meteorological data, a better constraint on volcanological input parameters like the height of the eruptive column and improving our understanding of processes such as aggregation phenomena and volcanic cloud microphysics.

Keywords: volcanic aerosol dispersal; 2001 and 2002 Etna eruptions; MISR; FALL3D model; 3D plume reconstruction; model validation.

1. Introduction

Explosive volcanic eruptions can eject large quantities of particles that remain airborne in the atmosphere for long periods of time and form volcanic clouds [Rose *et al.*, 2001]. Due to their impact on air traffic [e.g., Prata, 2009], a crucial aspect in terms of prevention and forecasting is the prompt assessment of the column height and plume extent. Column height serves to evaluate mass eruption rate which provides an indication of eruption intensity [Pyle, 2000], identify the area potentially affected by ash fallout [e.g., Carey and Sparks, 1986], and initialize tephra dispersal models [Mastin *et al.*, 2009]. In turn, the extent of the volcanic cloud delimits the current hazardous area and may be used to infer important characteristics of the eruption using backwards trajectory models. Cloud height estimations can be obtained from observations on the ground or by plane [e.g., Andronico *et al.*, 2008], radar measurements [e.g., Lacasse *et al.*, 2004], or satellite retrievals [e.g., Prata and Grant, 2001]. However, important discrepancies may occur among different observational methods [e.g., Tupper and Wunderman, 2009] as each methodology takes different phenomena into consideration [Mastin *et al.*, 2009].

Volcanic Ash Advisory Centers (VAACs) and some Volcano Observatories make a combined use of satellite images and volcanic ash transport and dispersion models (VATDM) in order to detect and track ash clouds and forecast the regions affected by ash dispersal [e.g., Peterson and Dean, 2008; Scollo *et al.*, 2009]. Ash cloud forecasting can be hindered by a number of factors. Firstly, it is clear that the reliability of a forecast depends on the accuracy of the VATDM inputs, which rely on other models (e.g., meteorological models) or on measurements and retrievals. For example, the presence of hydrometeors can prevent remote sensing instruments from detecting volcanic ash and, in some critical cases, hydrometeors completely mask the detection of ash clouds [Prata *et al.*, 2001]. On the other hand, accurate meteorological mesoscale forecasts may be unable to properly predict sudden wind variations and local circulation patterns in cases with complex topography and within the planetary boundary layer [Folch *et al.*, 2008a]. Furthermore, models simplify neglect some relevant physical aspects. For example, there is a low level of understanding of particle aggregation although this can have a dramatic effect on the dynamics of the cloud causing premature fallout of aggregates [Durant *et al.*, 2009] and formation of deposit secondary maxima [Rose, 1993]. Finally, it is worth noting that, as reflected in the post-event analysis of several explosive events, dispersal of tephra from a single eruption can be very complex [Watt *et al.*, 2009]. For example, eruptive style can alternate between weak and strong plumes causing different patterns of sedimentation [Bonadonna and Phillips, 2003; Bonadonna *et al.*, 2005] or the granulometry and composition of the erupted material [Andronico *et al.*, 2009] and mass eruption rate [Scollo *et al.*, 2007] may vary during the same eruption. The introduction of these variations in the models is very difficult and VATDM run with predefined or preliminary inputs which can differ substantially from those of the real eruption [Folch *et al.*, 2008b].

In order to achieve a robust forecasting we must validate ash dispersal models properly. Validation is usually carried out in two dimensions by comparing numerical simulations with ground-based data collected after the eruptive event [Bonadonna *et al.*, 2002; Scollo *et al.*, 2008a] or with satellite images showing the extent of the ash cloud [e.g., Barsotti *et al.*, 2008]. Although relevant, two-dimensional vertically-integrated data do not provide information on the extent and concentration of volcanic plumes at different heights. To date, measurements of 3D plume properties are very scarce. An initial attempt was carried out by Glaze *et al.* [1999], who interpreted the brightness temperature variation of satellite images as a change of the surface normal inclination and extracted the eruption plume height at different points. In this sense, Multi-angle Imaging SpectroRadiometer (MISR) can provide a novel mechanism to extract three-dimensional information on volcanic aerosol, in this work indicating the finest component of volcanic ash ($< 10 \mu\text{m}$).

The goal of this paper is twofold. The first goal is to investigate the potentiality of MISR as a tool to reconstruct 3D volcanic plume geometry. To this end, we use MISR data of two long-term Etna explosive eruptions occurring in 2001 and 2002. The second goal is to perform a 3D comparison between these data and the FALL3D atmospheric dispersion model [Costa *et al.*, 2006; Folch *et al.*, 2008a]. The manuscript is arranged as follows. Firstly, we overview the characteristics of the 2001 and 2002 Etna eruptions; secondly, we describe the modelling strategy including the MISR instrument, the retrieval procedure and the FALL3D dispersal model. Finally, we present the results and discuss the ability and limitations of the MISR volcanic cloud observations.

2. The 2001 and 2002 explosive activity of Etna

Mt. Etna is one of the world's most active volcanoes and, together with Sakurajima in Japan, Popocatepetl in Mexico, and Soufriere Hills in Montserrat Island, it is among the volcanoes that most frequently disrupt airport operations. Over the last twenty years, the explosive activity of Etna has increased in frequency [Branca and Del Carlo, 2005]. The recent explosive eruptions of 2001 and 2002 produced volcanic plumes reaching heights up to 6 and 7 km (a.s.l.) respectively, and forced the shut down of the Catania International Airport causing important economic damage at regional and national levels [e.g., Guffanti *et al.*, 2009].

The 2001 Etna eruption began on 17 July 2001 from a complex system of fractures that opened on the NE and S flanks of the volcano [Calvari *et al.*, 2001]. The eruption was heralded by a set of seismic swarms. From 12 July (at 21:44 UTC), 2645 earthquakes with magnitude $M_d \geq 1$ were recorded prior to the eruption onset, and the seismic activity continued throughout the eruptive period [Patanè *et al.*, 2003]. Lava flows were emitted on eastward the Valle del Bove and the southern slope of the volcano from seven fissures active over various periods of time [Calvari *et al.*, 2001]. The explosive activity, manifested as lava fountaining and strombolian activity, was mainly localized on the S flank. Two coalescent pit craters formed at 2570 m and produced the majority of the total ejected tephra between 19 July and 6 August [Scollo *et al.*, 2007]. This explosive activity had three distinct phases.

The first phase (from 19 to 24 July) was dominated by phreatomagmatic activity and produced an eruption column of oscillating height; the second phase (from 25 to 30 July) was characterized by purely magmatic activity, and the last phase showed characteristics of vulcanian eruptions [Taddeucci *et al.*, 2004]. The resulting tephra deposit was bilobate in shape and entirely covered the SE flank of the volcano. Scollo *et al.* [2007] estimated a total erupted mass between 1.02×10^9 and 2.31×10^9 kg applying the exponential [Pyle, 1989] and power-law [Bonadonna and Houghton, 2005] methods, respectively. The total grain-size distribution was evaluated with the Voronoi tessellation method [Bonadonna and Houghton, 2005], showing a mode of 2ϕ (where ϕ is $-\log d$ being d the particle diameter in *mm*).

The 2002 Etna eruption was one of the most spectacular events in the last years. The eruption began during the night of 26 October 2002 from two fissures opened on the NE and S flanks followed by a third fissure on the NE flank [Andronico *et al.*, 2005]. Like the 2001 event, a swarm of earthquakes preceded and accompanied the formation of eruptive fissures. The INGV-CT seismic network recorded 862 earthquakes ($M_d \geq 1$) until the eruption ceased on 28 January 2003 [Monaco *et al.*, 2005]. Two lava flows formed along the NE fissures; the first was directed towards the NE and stopped after 2.8 km, the second was directed towards the E and stopped after 6.8 km on 3 November, destroying most of the Piano Provenzana tourist infrastructure. The eruptive activity at the S fissure lasted up to 28 January 2003 and was characterized by lava fountains forming high eruption columns, strombolian activity, and lava effusion directed towards the SW and S [Andronico *et al.*, 2005]. During the first days of activity weak plumes rose up to 7 km in height [Andronico *et al.*, 2008]. Plumes were composite because different eruption columns from different vents merged to form a single plume or, more rarely, two plumes with different heights. Furthermore, the explosive activity produced lava fountains rising up to 600 m and magma jets appearing at a frequency of about 20-30 s [Andronico *et al.*, 2008]. After this sustained initial intensity, explosive activity diminished and formed very diluted or pulsating volcanic plumes. The maximum column height was about 7 km on 28 October, the mass and the total grain-size distribution evaluated by the analysis of the deposit were $4.4 \pm 0.6 \times 10^{10}$ kg and 0.5ϕ , respectively [Andronico *et al.*, 2008]. Table 1 summarizes the main characteristics of 21-24 July 2001 and 27 October 2002.

3 Methods

3.1 MISR data

3.1.1 The Multi-angle Imaging SpectroRadiometer

MISR is one of the instruments on board the Terra spacecraft, which is part of NASA's Earth Observing System (EOS) [Diner *et al.*, 1998]. Terra follows a near-polar, 705 km sun-synchronous orbit, crossing the equator at approximately 10:30 AM local solar time. The swath width has been designed to be 360 km, so that full coverage of a latitude circle is achieved every 9 days at the

equator and every 2 days near the poles. Nine separate cameras gather data in four spectral bands centered at 446.4, 557.5, 671.7, and 886.4 nm, corresponding to blue, green, red, and near-infrared wavelengths respectively. One camera points towards the nadir and the other eight provide forward and aft view angles of 26.1°, 45.6°, 60.0°, and 70.5° displaced in a symmetrical arrangement with respect to the nadir camera. MISR has a global coverage of +/- 82° latitude and provides 275-m sampling in all bands of the nadir camera and in the red bands of the off-nadir cameras [Muller *et al.*, 2002], whereas the rest of channels have 1.1 km resolution [Kahn *et al.*, 2001; Moroney *et al.*, 2002; Muller *et al.*, 2002]. On-board calibration is performed monthly by multiple in-flight methodologies, and the uncertainty in absolute radiometric accuracy is estimated to be 3% [Diner *et al.*, 1998].

Since 2000, MISR has provided a unique opportunity to study aerosol dispersal and short wave radiative properties [Diner *et al.*, 2001]. MISR products incorporate a set of aerosol models that are considered to be representative of different aerosols present in the Earth's atmosphere [Diner *et al.*, 2005]. MISR distinguishes different types of clouds, land surface cover and aerosol [e.g., Di Girolamo and Wilson, 2003; Kalashnikova and Kahn, 2006]. The aerosol retrieval is based on some assumptions and physical constraints [Martonchik *et al.*, 1998]: aerosol distribution is assumed horizontally homogeneous within 17.6 km x 17.6 km region at the surface and retrievals are carried out by comparing observed radiances with pre-computed model radiances obtained from predefined aerosol mixtures (combinations of up to three individual aerosol components). The retrievals are based on the best fit between the observed and model spectra, as determined by chi-square statistical tests. Aerosols considered in the MISR retrieval are sea spray (salt), sulfate/nitrate particles, mineral dust, biomass burning particles [Kahn *et al.*, 2001; Kalashnikova and Kahn, 2006].

3.1.2 The MINX software

For the purposes of this study, MISR data were analyzed using a program named MINX (MISR iNteractive eXplorer) which was designed to analyze smoke, volcanic and dust plume heights [Nelson *et al.*, 2008]. MINX provides height and wind retrievals at higher resolution and often with greater precision than the standard MISR retrievals. A stereo-matching technique compares red-band data between each of six off-nadir cameras and the nadir or reference camera. The technique matches similar features at a scale of a few hundred meters to determine the apparent offsets, or disparities, in the position of these features in the multiangle imagery and then uses this information to compute feature height and the wind vectors in the cross-track and along-track directions at these heights. Because the motion direction is provided by the user, when a plume is digitized, the number of unknowns is reduced from three to two: plume height and the ratio of speed across to speed along-track. The vertical precision of this method can be a few hundred meters under good conditions (David Nelson, personal communication). However, various factors such as cloud contamination, plume turbulence and low optical thickness can degrade retrieval quality. In particular, retrievals are difficult when the direction of plume motion is parallel to the along-track direction of the spacecraft.

Furthermore, wind is an important factor in the stereo-matching process because the disparity can be a combination of the parallax, due strictly to geometry, and an actual shift in a cloud location due to winds [Martonchik *et al.*, 2009]. MINX retrieves the wind vector at a specific height known as the “no wind-corrected heights” and, for the wind retrieval that pass a quality assessment, derives a “wind-corrected height”. For this reason, the no wind-corrected heights are less accurate but they have a more complete coverage (see details in <https://www.openchannelsoftware.com/projects/MINX>). In addition to height, MINX generates estimates of aerosol optical thickness (AOT) or aerosol optical depth (AOD) (i.e. the extinction coefficient integrated over a vertical column of unit cross section from the Earth’s surface to the top of the atmosphere), Angstrom exponent (A) (i.e. exponent of power law representation of extinction versus the wavelength, usually inversely related to the average size of the aerosol particles), and single-scattering albedo (SSA) [Diner *et al.*, 1998] the ratio of scattering efficiency to total light extinction. Finally, MINX gives the fraction of the green-band optical depth value attributable to small ($<0.35 \mu\text{m}$), medium ($0.35 < 0.7 \mu\text{m}$), and large ($>0.7 \mu\text{m}$) particle sizes, and the fraction of the green-band optical depth value attributable to spherical particles (Tau Fraction by Particle size). It is important to note that the detection limit for particle size is strictly linked to the aerosol components available in the MISR retrieval algorithms. Aerosols are modeled using lognormal particle size distributions, characterized by the median radius and the standard deviation [Kahn *et al.*, 2001; Kalashnikova and Kahn, 2006], having larger particles with a mean radius of $2 \mu\text{m}$ and standard deviation of 2. Furthermore, MISR is more sensitive to particles between 0.05 to $2 \mu\text{m}$ in diameter [Kahn *et al.*, 1998] although studies have been carried out also including particles $< 10 \mu\text{m}$ [e.g., Jiang *et al.*, 2007]. Here, we assume $2.5 - 10 \mu\text{m}$ as the largest particle size detected by MISR. Hence, although volcanic clouds contain a mixture of gases (e.g., water, carbon dioxide, sulphur dioxide), aerosol (a dispersion of small ($< 10 \mu\text{m}$) solid or liquid particles in a gas medium), and silicate ash particles (particles up to $2000 \mu\text{m}$), in this study we are only consider the fraction of particles $< 10 \mu\text{m}$. However, it is highlighted that the finer particles are able to reach major distances from the volcanic vent and this size ($< 10 \mu\text{m}$) is considered the most dangerous in terms of aviation hazard assessment.

3.2 Ash cloud modelling

The modelling strategy is based on coupling a meteorological mesoscale model, a volcanic plume model based on the Buoyant Plume Theory (BPT) to describe the eruptive column [Bursik, 2001; Carazzo *et al.*, 2008], and the FALL3D atmospheric dispersion model [Costa *et al.*, 2006; Folch *et al.*, 2008a].

3.2.1 WRF

The Weather Research and Forecasting (WRF) model is a fully compressible, Eulerian non-hydrostatic mesoscale meteorological model that solves equations of atmospheric motion [Michalakes *et al.*, 2005]. Here, we use WRF to reproduce the meteorological conditions from 20 July 2001 at 18 UTC to 26 July 2001 at 00 UTC and from 26 October 2002 at 12 UTC to 28 October 2002 at 00 UTC respectively. These time intervals cover an initial WRF spin-up period and the duration of the plume dispersal simulations. The WRF model was configured to integrate the primitive equations using the ARW (the Advance Research WRF) dynamics solver [Skamarock *et al.*, 2005] in three high-resolution nested domains (horizontal resolutions of nests are 18, 6, and 2 km respectively), with 40 vertical layers, and centered over western Sicily. We fixed the top pressure of the WRF model to 10 hPa. Initial and 6-hourly boundary conditions for WRF were obtained from the Global Forecast System (GFS) re-analysis at 2.5° resolution. We tested the accuracy of the WRF results by comparing the simulated wind vertical profiles with atmospheric soundings at the nearest world meteorological station (Trapani, about 220 km W from Etna). Figure 1 shows simulated and measured vertical profiles of wind speed and direction at Trapani on 22 July 2001 (06UTC) and 27 October 2002 (06UTC). In general, there is a good agreement between soundings and WRF results except in the planetary boundary layer below 2-3 km, where differences of a few m/s and from 10° to 30° are typically observed for wind velocities and wind directions respectively.

3.2.2 FALL3D

FALL3D [Costa *et al.*, 2006; Folch *et al.*, 2008a] is an Eulerian model which simulates the transport and deposition of volcanic ash. The model solves the advection-diffusion-sedimentation equation with turbulent diffusion given by gradient transport theory, a class-dependent particle terminal velocity model, and a time-dependent three-dimensional wind field furnished by global or mesoscale meteorological models like WRF. The model accounts for terrain effects and can deal simultaneously with a wide spectrum of particle sizes (from lapilli to very fine ash) and gas components (e.g., H₂O or SO₂). The main volcanological model inputs are mass eruption rate, total grain-size distribution, height and shape of eruption column. FALL3D has already been validated against ground data and/or MODIS images for the 2001 Etna eruption [Costa *et al.*, 2006], and for other eruptions [e.g., Folch *et al.*, 2008b]. The model runs daily at INGV-CT and the results are used to forecast plume dispersal during Etna explosive events [Scollo *et al.*, 2009]. Here, we couple the FALL3D model with the hourly WRF meteorological fields following an off-line strategy to simulate the 22 July 2001 and 27 October 2002 eruptive events.

4. Results

The chemical, physical and optical characteristics of volcanic aerosols erupted during 2001 and 2002 Etna eruptions have been characterized using both ground-based and remote sensing systems [e.g., Pappalardo *et al.*, 2004; Wang *et al.*, 2008; Filizzola *et al.*, 2007]. However, the MISR data acquired

over Etna during these eruptions gives an opportunity to reconstruct the volcanic plume geometry and compare MISR stereoscopic retrievals with numerical simulations. It is important to state that the inputs for the dispersal model have been obtained from field studies and observations that are absolutely independent of MISR retrievals.

4.1 MISR Retrievals

During the first phase of 2001 Etna eruption, MISR detected the Etna volcanic plume on 22 July 2001 at about 10:00 UTC. Stereoscopic wind-corrected heights are shown in Figure 2 and indicate a narrow SE directed plume extending for more than 200 km downwind. The image reveals the presence of volcanic aerosol at different heights along the volcanic plume, with higher and lower heights to the right and left of the main axis respectively. These differences, as retrieved by MINX, may be attributed to variations of wind direction as a function of the height.

Figure 3 shows wind-corrected heights as a function of the distance from the vent. The detected top-heights of the volcanic plume are around 6 km at about 70 and 150 km away from the vent. Moreover, the figure shows a bent-over shape of the plume near the source due to wind action and an increase of volcanic particles in the lower part of the plume. This could be explained by the emission of ash at different heights along the eruptive column but also as a result of an abrupt decrease in particle settling velocity occurring at the plume-air interface [Carey, 1997]. The latter causes the formation of fingers, which were observed during 2001 and 2002 Mt. Etna eruptions. Figures 2 and 3 highlight the difficulties of MISR in detecting particles at about 25 and 175 km from the vent due to the presence of clouds.

Figure 4 shows the stereo height histograms of the volcanic plumes at four selected regions located at 100, 150, 200, 250 km from the volcanic vent. The retrieved plume heights are between 5 and 5.5 km in the first region (100 km from the vent) remaining constant in the second region (150 km from the vent). However, the heights decrease to 4.5-5 km and 4-4.5 km in the third region (200 km from the vent) and in the fourth region (250 km from the vent), respectively. It follows that, according to the MINX retrieval, the height of the 2001 volcanic plume decreased approximately by 1 km along the main plume axes (SE) in about 250 km. Assuming a wind speed of 10 m/s (an average of the WRF results at that height), the resulting settling velocity should be of around 4 cm/s. This is consistent with the Stokes terminal velocity law for a sphere of diameter 20 μm and density of 2.5 g cm^{-3} but it is two orders of magnitude larger than the theoretical value for a sphere of 2 μm in diameter.

Finally, we also retrieved AOD between 0.07 and 0.27 with a mode equal to 0.12-0.13, a fraction of spherical particles of only 2%, a SSA_{558} value is 0.97 ± 0.2 , and an Angstrom coefficient between 0.4 and 1.7.

Figure 5 shows the imagery and the wind-corrected heights of the nadir camera of the volcanic plume retrieved on 27 October 2002 at 10:00 UTC. The volcanic plume is directed toward SSE and covering a region wider than the 2001 Etna plume. Volcanic aerosols are above 4500 m toward the SSW and

below 4500 m towards the SSE with more pronounced differences in height much than in the 2001 image (see Figure 2). In this case, we interpret this as the result of multiple sources that formed a composite plume dispersed along two different axes.

Figure 6 shows the wind-corrected heights as a function of the distance from the vent. The top plume height is approximately 6 km near the vent and reaches a maximum of 7 km at about 70 km downwind. This is in good agreement with the observations reported by Andronico et al. [2008]. It should be noted that the 27 October 2002 explosive activity was more intense than the 22 July 2001 activity, resulting in a volcanic plume having a slight bent-over shape due to the minor effect of wind on the eruption column.

Histograms of MINX stereo heights at four regions located at 50, 150, 200 and 250 km from the vent are given in Figure 7. The region at 100 km from the vent was not considered because of few MINX data retrieved at this distance. The heights obtained by MINX are mainly between 5 and 5.5 km at the first region (50 km from the vent) and stay constant to 3-4 km in the next regions (from 150 to 250 km). This is inconsistent with the Stokes terminal velocity law for a sphere of diameter 10 μm and density of 2.5 g cm^{-3} . Finally, we retrieved AOD ranging between 0.025 and 0.95 with a mode between 0.39 and 0.4, a distribution composed mainly by medium and large size particles with a 3% of spherical particles, a value of SSA_{558} of 0.97 ± 0.2 , and an Angstrom coefficient ranging between 0.04 and 1.3.

4.2 FALL3D simulations

We set the eruption source parameters (the date of onset, the duration of the eruption and run, the mass eruption rate and the total gain-size distribution) in FALL3D (Table 2). For the 2001 eruption, the modelling study focuses on the first phreatomagmatic phase, spanning the period from 21 July at 00 UTC to 25 July at 00 UTC. For simplicity, mass eruption rate was assumed to be constant for each day, with daily values ranging between 2.5 and 7.5 $\times 10^3$ kg/s. The total erupted mass is 1.7 $\times 10^9$ kg, a value very close to the 2.3 $\times 10^9$ kg found by Scollo et al. [2007]. We considered a 9 particle class Gaussian distribution ranging from -2 ϕ (4mm) to 7 ϕ (8 μm) and peaked at 2 ϕ (0.25 μm). The simulated fallout deposit is first emplaced towards the E on 21 July and then directed towards the SE on 22 July. The increase of the eruption intensity on 23 July (when the column reached the maximum height) caused a larger amount of tephra deposit on the SE flanks of the volcano (see Figure 8). The simulated deposit looks very similar in shape to that observed in the field [Scollo et al., 2007, Figure 7], but off by a few degrees. We attribute this difference mainly to the errors in the simulated wind field direction, which are larger within the PBL, where most of the transport occurred.

For the 2002 case, we model the first day of the eruption (from 26 October 21 UTC to 27 October 10 UTC) and compare the results with field data collected on the ground [Andronico et al., 2008]. Based on observations of explosive activity, we assigned a column height of 6000 m (± 500 m), for which the BPT gives an averaged mass eruption rate of about 4 $\times 10^4$ kg/s. As in the 2001 case, we also

assume 9 particle classes but with the Gaussian distribution peaked at 0.5ϕ (reflecting the magmatic nature of the 2002 event). The plume drifted SE at the beginning of the eruption and towards the SSW early in the morning of 27 October. The computed deposit (Figure 9) shows a good agreement with field data [Andronico *et al.*, 2008, Figure 4a].

4.3 Comparisons between MISR Retrievals and FALL3D Simulations

Figure 10 shows FALL3D concentration contours at 4000 and 5000 m superimposed on MINX results for 22 July 2001. In order to be consistent with the MISR aerosol size detection threshold only the finest granulometric classes of FALL3D ($< 10 \mu\text{m}$) are plotted. It is notable as all particles retrieved by MINX are inside the 10^{-4} g m^{-3} isoline. A difference of about 10° occurs at 5000 m between MINX results and the simulated plume dispersal axis. This discrepancy is likely caused by poor forecasting of the wind direction. Figure 11 compares MINX stereo height histograms of the plume at the four selected regions with normalized vertical concentration profiles simulated by FALL3D. Assuming that the number of particles per pixel is similar, the frequency histogram (i.e. the percentage of pixels with a given retrieved height) is proportional to the variation of concentration with height and hence can be directly compared to a normalized concentration. This gives information about the measured versus simulated volcanic cloud height, thickness and shape. The differences are near the MISR resolution limit (500 m). Furthermore, the agreement between stereo height histograms and simulations improves on moving away from the volcanic vent (compare regions at 50 and 200 km in Figure 11). It is highlighted that while MINX retrievals detected variations of volcanic ash heights at different distances from the vent, the vertical concentration profiles almost maintain the same height.

Figure 12 compares simulated concentration contours with MINX retrieval at 4000 and 5000 m for 27 October 2002. All MINX results fall inside the 10^{-5} g m^{-3} isoline and the differences in the direction of the plume are of about 15° . This difference is too large to be attributed only to inaccurate forecasting, and reinforces the hypothesis of multiple sources (not contemplated by the model). Finally, Figure 13 shows the MINX stereo height histograms superimposed on simulated vertical concentration profiles for the selected regions, located at 50, 150, 200 and 250 km from the volcanic vent. As in the 2001 case, the variations of volcanic aerosol detected by MISR are not captured in the simulations. However, some of these variations could be attributed to ambiguity caused by the nearly along-track direction of plume motion.

5. Discussion

The application of MISR to volcanic plumes seems to be promising. Indeed, volcanic plumes constitute a good target for space-based MISR instrumentation because the sources can remain active for long periods at fixed geographic locations and, moreover, the properties of volcanic fine ash are very distinctive from those of aerosols in the surrounding atmosphere [Kahn *et al.*, 2007]. Our

opinion is that MISR may really become a very useful tool to study volcanic clouds and to mitigate its hazardous effects. Nowadays, volcanologists make use of pre-defined eruptive scenarios to evaluate the potential impacts of volcanic clouds and tephra fallout at regional level [Mastin *et al.*, 2009]. For example, everyday INGV-CT simulates three eruptive scenarios of Mt. Etna similar to the 1998, 2001 and 2002 eruptions. The results are automatically delivered to the civil protection and aviation authorities to be eventually used as a first assessment of the volcanic ash plume impact [Coltelli, 2006; Scollo *et al.*, 2009]. In case of a real eruption, an important aspect in terms of mitigation is to discriminate, as quickly as possible, which of the simulated scenarios matches the actual eruption. Combined with other classical techniques, MISR could be an aid for this purpose. On the other hand, during an on-going explosive eruption, VATDM are also used by VAACs and volcano observatories to forecast trajectories of volcanic clouds and to estimate the expected short-term fallout. Regardless of the framework and the modelling strategy, the assessment of the eruptive parameters like column height, erupted mass and the granulometric distribution of particles, is important in order to improve the reliability of models. In fact, model sensitivity analysis [e.g., Connor and Connor, 2006; Scollo *et al.*, 2008b] has demonstrated that these parameters are amongst the most influent input data of tephra dispersal models. We argue that a syn-eruptive assimilation of MISR data into models would represent an important step forward to improve volcanic cloud forecasting.

However, we point out that there are a number of limitations including such as: MISR sensor views a relatively small portion of Earth at a single time and captures images of individual sites only about once per week [Kahn *et al.*, 2007]. It follows that it cannot be used as a “continuous” monitoring system as MODIS, AVHRR, or SEVIRI; MISR standard algorithm can fail in presence of clouds. Moreover, as pointed out by Moroney *et al.* [2002], the stereo-matching retrieval algorithms can also fail in multi-layered cloudy scenes, resulting in low quality MISR’s cloud-top height retrieval. Afterwards, we describe the ability and limitation on volcanic cloud height and aerosol retrievals and on the modelling strategy used in this paper.

5.1 Ability and Limitation on Height Retrieval

Today, several remote sensing or ground-based techniques are used to measure or to infer heights of volcanic plumes. Instruments like radar [e.g., Lacasse *et al.*, 2004] and lidar [Sassen *et al.*, 2007] are potentially suitable for this purpose. Other common strategies are to compare plume top infrared brightness temperatures (BT) with atmospheric profiles [e.g., Holasek *et al.*, 1996; Sawada, 1987, Wen and Rose, 1994] or to determine the height at which the ascent velocity of the volcanic plume equals the incident wind [e.g., Tupper *et al.*, 2004]. Alternatively, geometric techniques can also be used whenever the shadow of the plume is visible on the underlying Earth’s surface [Holasek *et al.*, 1996; Prata and Grant, 2001] or even on meteorological clouds [Oppenheimer, 1998]. More recently, Richards *et al.* [2006] applied the MODIS CO₂ slicing algorithm (which uses five MODIS infrared bands) to measure eruption column heights of several explosive eruptions. Here, we propose the

space-based multiangle and multispectral MISR imaging as an alternative, novel, and powerful mechanism to study volcanic plumes. In fact, we found MISR data are in good agreement with observations collected during monitoring activities of INGV-CT. However, MINX retrieved heights and observations may differ due to a number of reasons. For example, differences could exist in case of oscillating columns if the precise instant of the MISR overpass does not coincide with the instant of the photo shot. Discrepancies could be due to the different dynamic regimes of the finer particles which may continue to rise due to buoyancy effects [Bonadonna and Phillips, 2003] resulting in MISR overestimating heights with respect to observations.

The sensitivity and accuracy of the MISR stereo heights have already been validated against radar and lidar ground truth for meteorological clouds [Moroney *et al.*, 2002; Naud *et al.*, 2002, 2004, 2005]. MISR versus lidar comparisons [Naud *et al.*, 2004] has shown that differences in measured heights range from 0.1 to a maximum of 0.4 km. We argue that similar results should be expected for volcanic plumes given the geometric nature of the retrieval method; that is to say, MISR and lidar should have a similar accuracy when they are applied to volcanic plumes. Thus, MISR data can be used in combination with other remote sensing (e.g., MODIS) or ground (e.g., lidar) techniques to evaluate eruption column heights with higher precision [Genkova *et al.*, 2007]. This opportunity could bring a great advancement on the quality of tephra dispersal forecasting.

5.2 Ability and Limitation on Aerosol Retrieval

It is highlighted that MISR spectral range is sensitive mainly to aerosol particles of about 2.5 μm in diameter. In many volcanic eruptions, the mass fraction of fine ash with diameter lower than 2.5 μm is typically low, although this value varies widely depending on factors like magma composition or the occurrence of magma-water interaction [Rose *et al.*, 2000]. It is clear that the mass fraction of the volcanic plume viewed by MISR will increase with distance, when larger constituents are removed. However, on the base of the total grain-size distribution carried out during 2001 and 2002-03 Etna eruptions, MISR should detect about 1% of the total erupted volume/mass for both eruptions.

Furthermore, Kalashnikova *et al.* [2005] demonstrated that MISR can be used to extract granulometric information of the finest plume components. Our analysis pointed out that the majority of particles detected by MISR belong to the medium (between 0.35 and 0.7 μm diameter) and large classes (larger than 0.7 μm) for 2001 and 2002 volcanic plumes, respectively. This is also consistent with the style of the explosive activity derived from the analysis of the deposit. In fact the total grain-size distribution of the 2001 eruption peaked at 2 ϕ mainly due to magma-water interaction [Scollo *et al.*, 2007]. In contrast, the 2002 eruption was a purely magmatic type and generated a distribution of particles with a higher mean diameter, peaking at 0.5 ϕ [Andronico *et al.*, 2008]. It is highlight that aerosol products, other than the aerosol optical thickness and plume height are not validated globally [Khan *et al.*, 2007] and consequently these values should be taken only qualitatively. If no wind-corrected heights are used, a greater number of points are detected by MISR. However, we found

differences of only 8% and 30% using wind corrected heights compared to no wind-corrected heights for 2001 and 2002 Etna eruptions respectively.

5.3 Ability and Limitation on Modelling

MISR has already been used to validate aerosol dispersal simulations [Stenchikov *et al.*, 2006], also in combination with AERONET data [Solomon *et al.*, 2006; Liu *et al.*, 2004] and in this paper to validate tephra dispersal models. We found that ash concentration values up to 10^{-5} g/m³ fit the MISR data for both 22 July 2001 and 27 October 2002 volcanic plumes. This threshold is in agreement with that used from VAAC of Montreal [Witham *et al.*, 2007] and could be used on hazard maps of models which forecast the ash dispersal in the atmosphere soon after the eruptive event. Furthermore, we pointed out that some discrepancies between MISR data and model results could be imputed to:

i) inaccurate meteorological forecasting, due to a lack of any meteorological and plume coupling [Costa *et al.*, 2006] and a less accuracy inside PBL where the complex topography of the volcano generates a more irregular wind field [Barsotti and Neri, 2008]; ii) uncertainties of the FALL3D modelled cloud heights that come from ground-observations and are rounded considering the error of the observations (20%) and the vertical grid resolution (250 m); iii) poorly understood processes such as particle buoyancy effects, aggregation processes, occurrence of particle loading and sublimation and evaporation of hydrometeors at the volcanic plume base which could verify into the plume [Durant *et al.*, 2009]; iv) high variability of the eruptive activity that prove difficult to introduce into the modelling mainly due to a lack of “continuous” monitoring system of volcanic plumes.

6 Conclusions and Future work

This work has shown that MISR can detect some features of volcanic plumes, like height and shape of the eruption column, and relevant characteristics of the finest components. A 3D comparison between MISR stereoscopic retrievals and numerical simulations using the FALL3D dispersal model indicates that the model is able to forecast the dispersion of ash properly providing that high-resolution meteorological data is available and that volcanological input parameters are well constrained. Column height is a key parameter, especially to model atmospheric concentration. In this sense, it is important to have ground and remote sensing techniques that can evaluate this parameter with high accuracy. Assimilation of MISR data into tephra dispersal models would improve its reliability and help to drastically reduce the threat to aviation.

Future work includes the validations of MISR aerosol products using data collected by several instruments which detected Etna volcanic plumes during the last eruptions such as: channel un-tracking photometer [e.g., Watson and Oppenheimer, 2000; 2001], Airborne Multispectral Imaging Spectrometer (MIVIS) [e.g., Spinetti *et al.*, 2003; Spinetti and Buongiorno, 2007; Remitti *et al.*, 2006], lidar instruments [Villani *et al.*, 2006; Fiorani *et al.*, 2009], Moderate Resolution Imaging Spectroradiometer (MODIS) [Corradini *et al.*, 2008], Advanced Visible and Near Infrared

Radiometer (AVNIR) [Oppenheimer *et al.*, 1998], aerosol spectrometers [Allen *et al.*, 2006]; satellite and ground-based instruments [e.g., Zerefos *et al.*, 2006]. In addition, tephra deposit could be evaluated by the MISR optical depth by applying techniques similar to those used by Liu *et al.* [2007] to predict ground-level PM_{2.5} concentrations in St. Louis in Missouri (USA).

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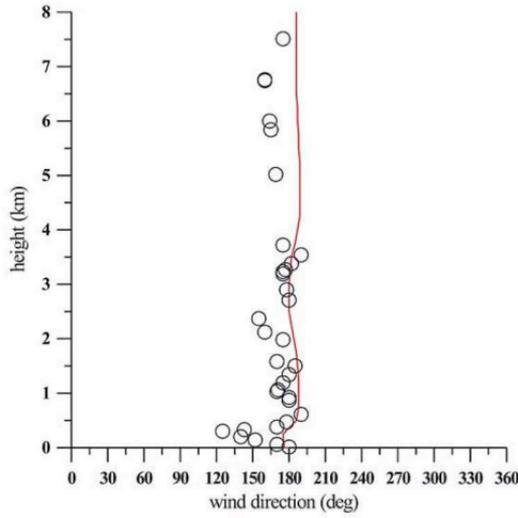
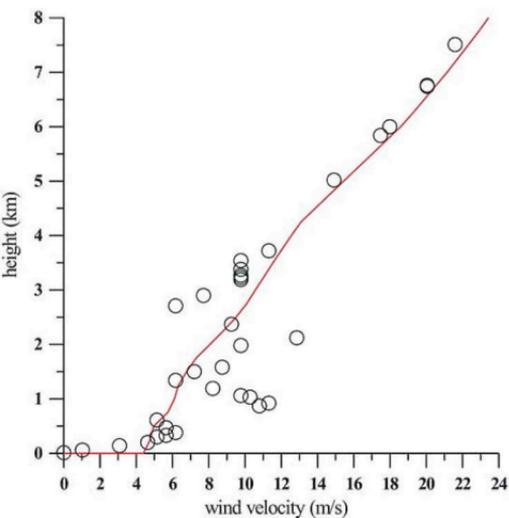
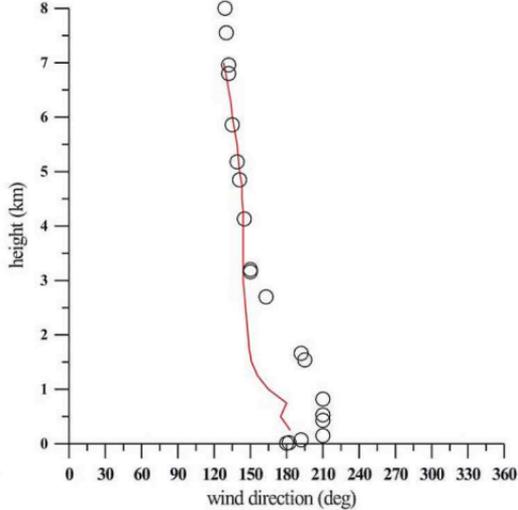
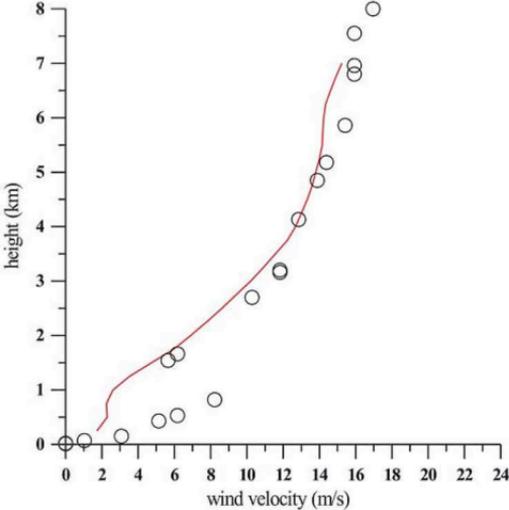
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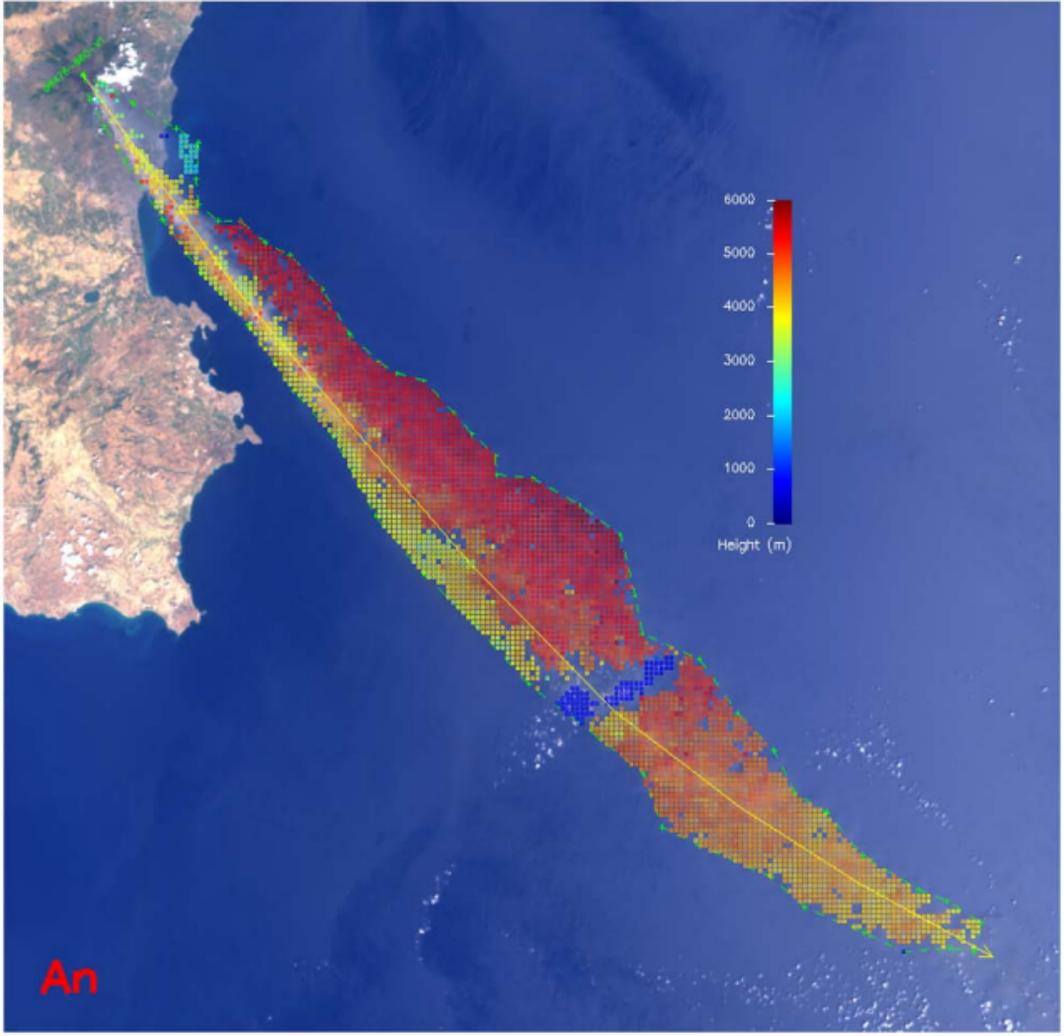
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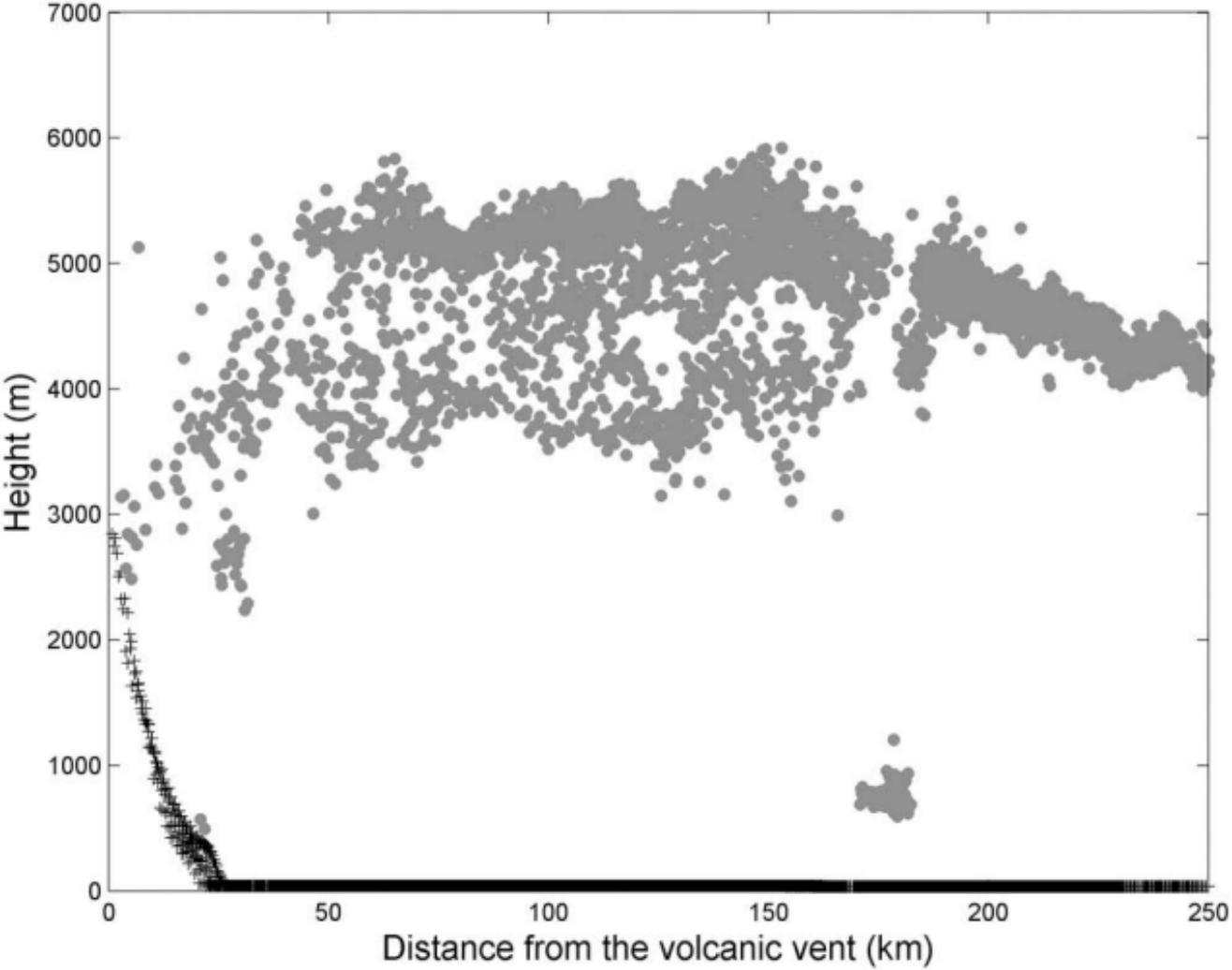
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Year	Day/Month	Vent location (m a.s.l.)	Characteristics of the explosive activity	Column Height	Total Mass	Mode of grain-size
2001	21 Jul.-24 Jul.	S flanks (from 3050 to 2100 m)	Violent strombolian activity; continuous ash emission; magma-water interaction; presence of aggregation.	21 July: 3.5-4 km 22 July: 3.5-4 km 23 July: 5 km 24 July: 4.5 km	2.3×10^9 kg	2 ϕ
2002	27 Oct.	S flanks (from 2850 to 2600 m)	lava fountaining; sustained eruption column; continuous ash emission.	6 km	0.9×10^9 kg	0.5 ϕ

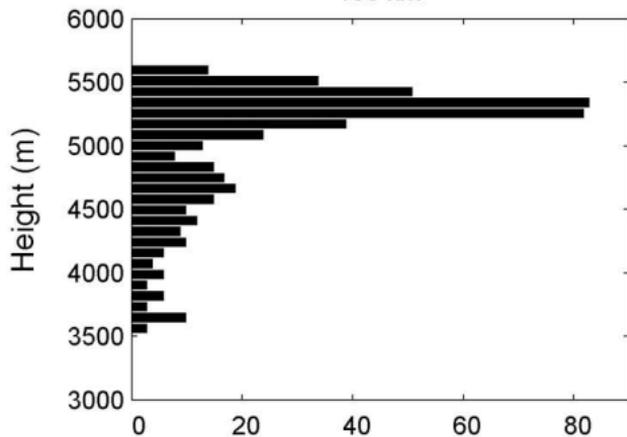
Year	Date of onset	Duration of the eruption	Duration of the run	Mass eruption rate (kg/s)	Total Grain-size Distribution
2001	21 Jul. 00 UTC	96 h	98 h	20 July: 2.5×10^3 kg/s 21 July: 2.5×10^3 kg/s 22 July: 7.5×10^3 kg/s 23 July: 7.5×10^3 kg/s	$2 \pm 1.5 \phi$
2002	26 Oct. 21 UTC	24 h	26 h	4.0×10^4 kg/s	$0.5 \pm 1.5 \phi$



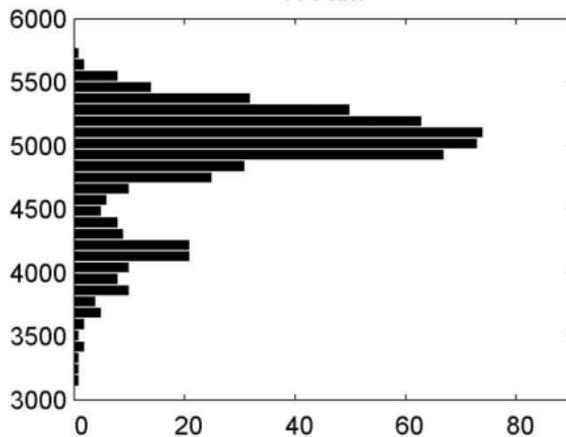




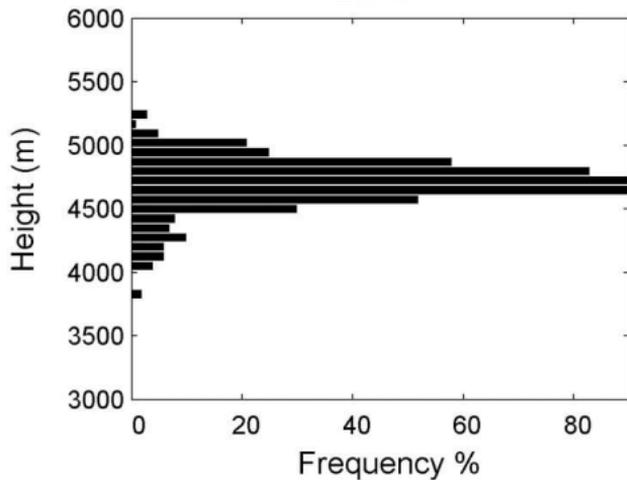
100 km



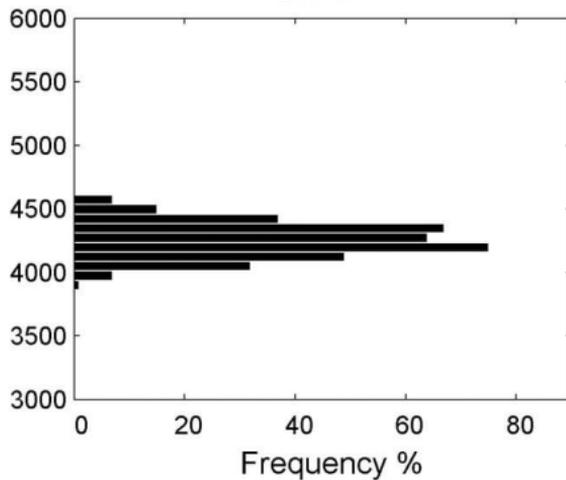
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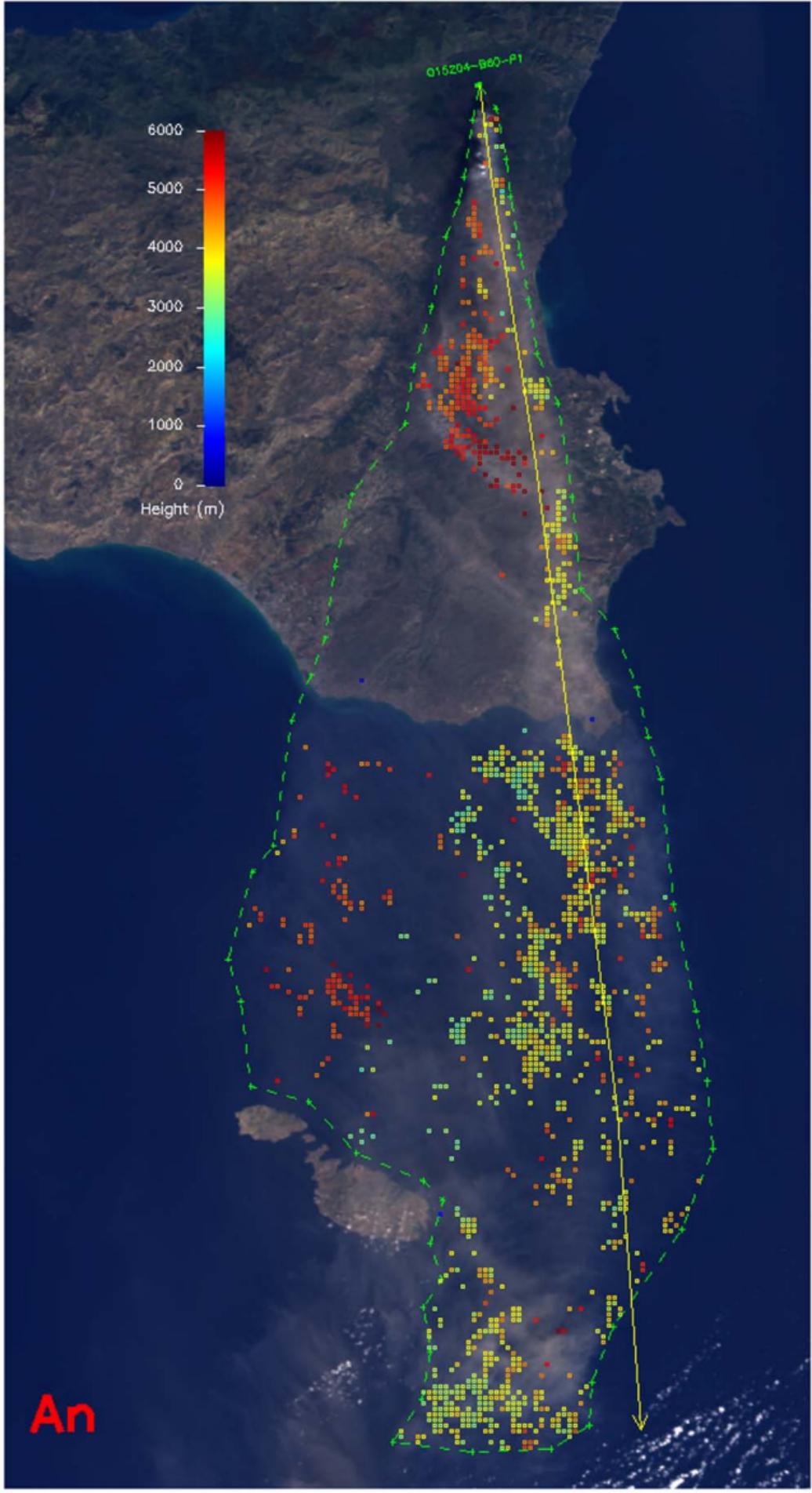


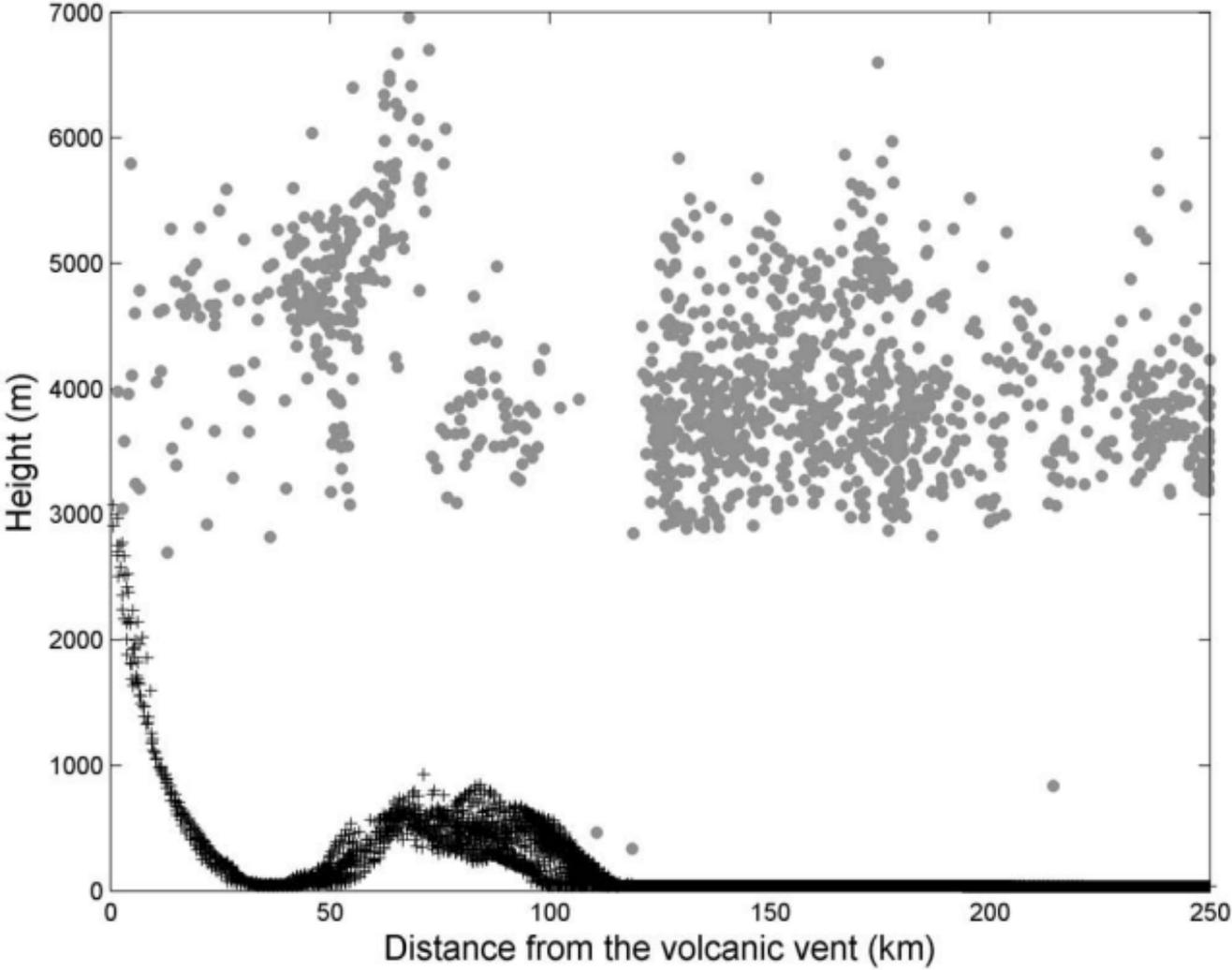
200 km

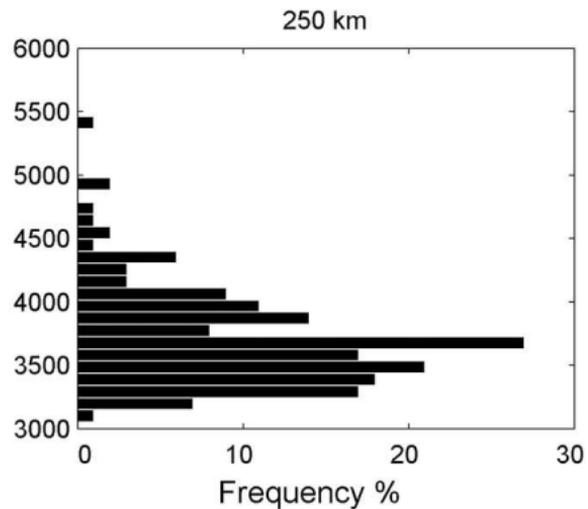
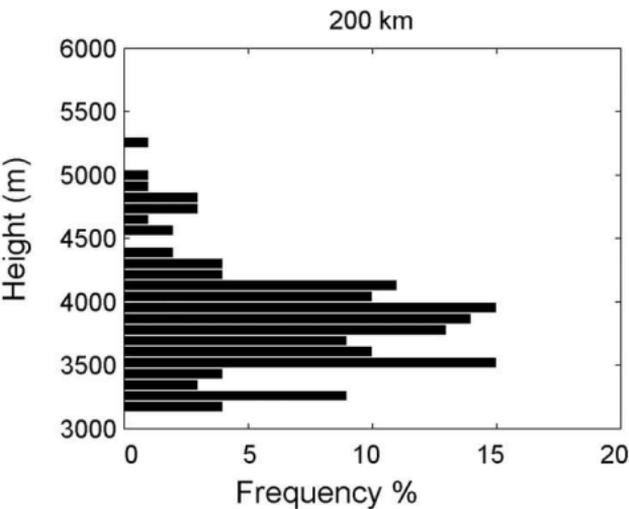
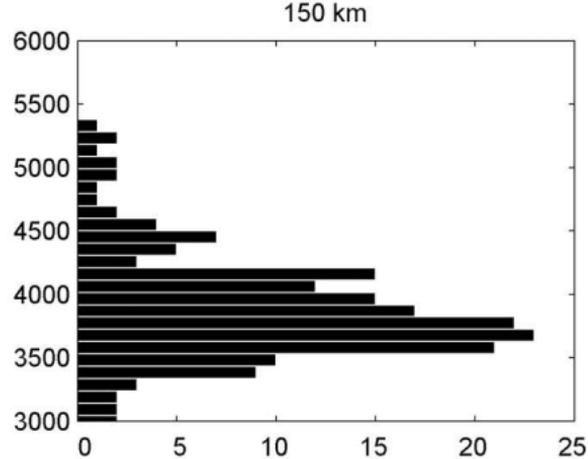
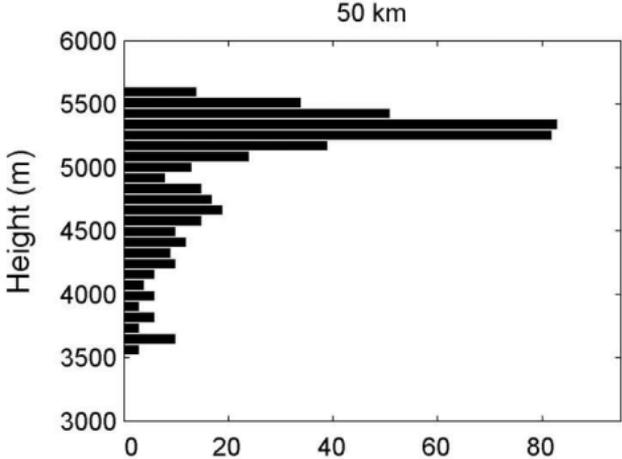


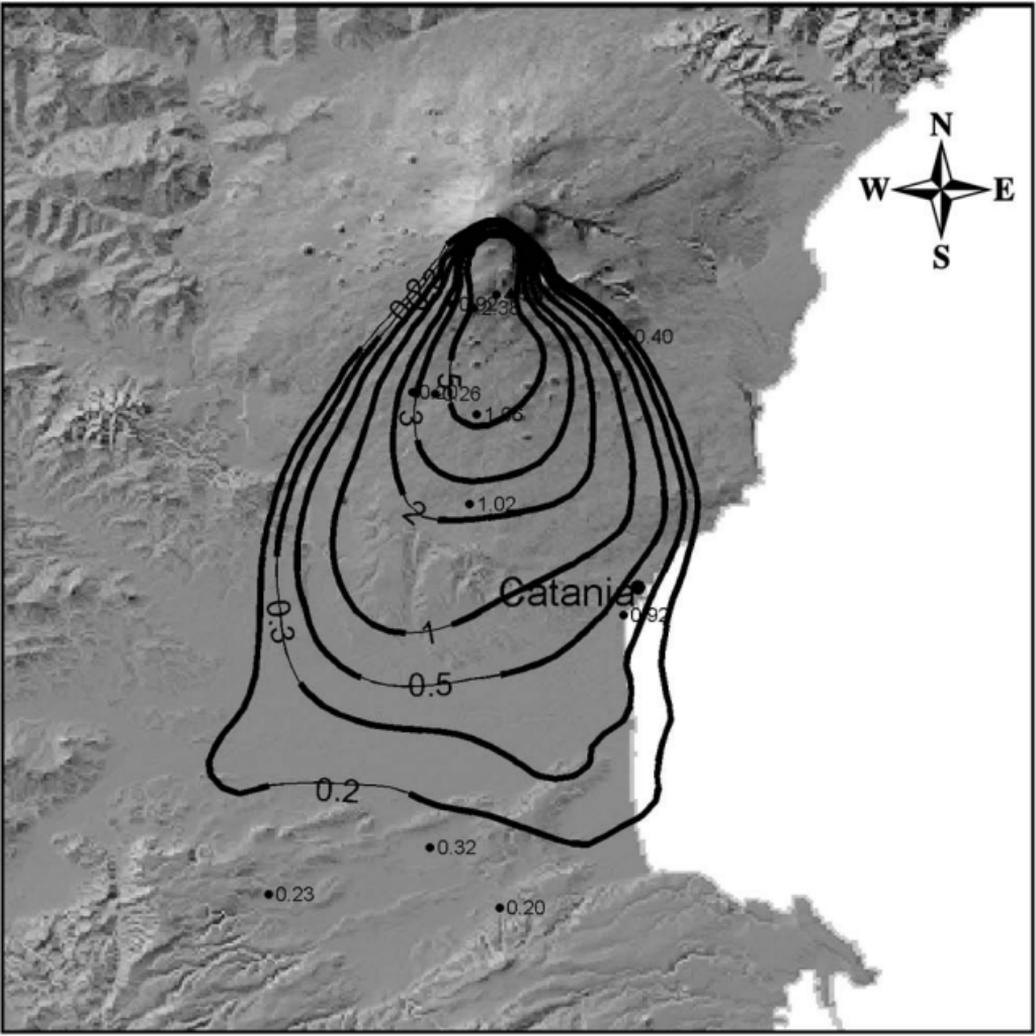
250 km

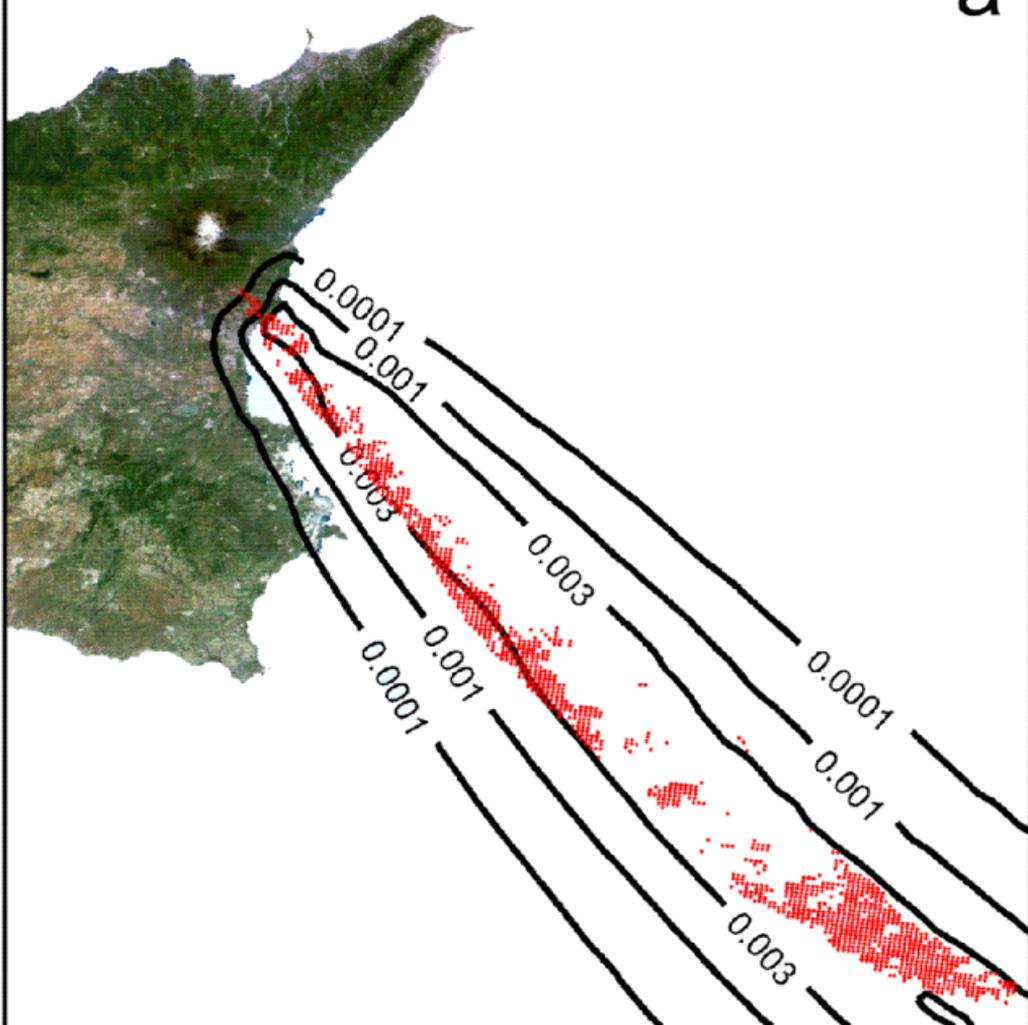










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