PM_{10} measurements in urban settlements after lava fountain episodes at Mt Etna, Italy: Pilot test to assess volcanic ash hazard on human health

Daniele Andronico[1], Paola Del Carlo[2]

1 Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo, Piazza Roma 2, 95125 Catania (Italy)

2 Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa, Via Della Faggiola 32, 56126 Pisa (Italy)

Abstract

~~In this paper, we focus on~~ We have made a preliminary study on the potential risks caused by the sub-10 μm ~~micron~~ fraction of volcanic ash (Particulate Matter: PM_{10}) after the basaltic explosive eruptions from Mt Etna volcano (Italy), which have dramatically increased in frequency over the last 20 years. We present results deriving from the study of the ash concentration in the air following the lava fountain episode from the New South-East Crater of Etna on 15 November 2011, which caused tephra fallout over the eastern slope of the volcano. Short-duration tests of PM_{10} measurements were carried out at three different sites using a TSI® DustTrak™ aerosol monitor a few hours after the end of the eruption, and readouts of the air quality were repeated at the same sites a month later without volcanic activity. Furthermore, ash samples were characterized by grain-size, componentry, morphological and petro-chemical analyses.

By comparing PM_{10} levels measured a few hours after the 15 November lava fountain and on 15 December, we found that relatively low amounts (500-1500 g m^{-2}) of tephra fallout cause high levels of PM_{10} in the air. This is because the coarse particles, particularly~~like~~ basaltic ash, are readily broken up by traffic and hence remobilized into the air. We believe ~~that in the future~~ the impact from ash fallout in the Etnean territory should receive greater~~proper~~ attention, especially regarding ~~in order to avoid~~ potential health problems.~~; this may be achieved by~~ ~~accomplishing implementing~~ S~~s~~imple but effective actions can be implemented to reduce eventual risks, first and foremost the prompt removal of the ash deposits from the urbanized areas.

Keywords: Mt Etna – lava fountain - volcanic ash – PM_{10} – air pollution - health hazard

1 Introduction

The effects of volcanic ash on people's health have been widely acknowledged and documented in the literature (e.g. Damby et al., 2013; Hincks et al., 2006; Horwell et al., 2003, ~~2006~~2007, 2010, 2013; Le Blond et al., 2010; Searl et al., 2002; Wilson et al., 2011). The finer particles, especially particulate matter with dimensions ≤10 μm ~~micron~~ or PM_{10} in aerodynamic equivalent diameter (i.e.~~,~~ the diameter of a spherical particle with density 1000 kg/m^3 and the same settling velocity as the airborne particle considered)~~(PM_{10})~~, remain suspended in the air and may be inhaled, causing different degrees of injury depending on the particle size (Horwell and Baxter, 2006). Coarse particles of 4–10 μm aerodynamic diameter ~~(i.e. PM_{10} and PM_4)~~ are also called 'thoracic' because they may reach the bronchioles of the lungs via the nose and throat, while fine (<PM_4 and $PM_{2.5}$) particles are called 'respirable' since they can more readily penetrate into the lungs, thus involving the alveolar region where the gas-exchanges take place (QUARG, 1996). The limit between thoracic and respirable particles at the sub-4 μm ash fraction also reflects the greater hazard from the fine particles during long-term exposure (Expert Panel on Air Quality Standards, 1995, 2001).

In the First "daughter" directive of the EU Air Quality Framework Directive (EC, 1999), the European legislation establishes the limit values of PM_{10} concentrations not to be exceeded over 24 hours and yearly for the protection of human health, i.e. 0.050 mg m^{-3} as the mean measured value over 24 hours which must not be exceeded more than 35 times per year and 0.040 mg m^{-3} as annual mean concentration. It is worth noting that the EU directive 99/30 (EU, 2008) had fixed January 1st, 2010 as the starting date from which more severe limits would have to be respected, i.e. a limit value of 0.050 mg m^{-3} should not be exceeded more than 7 times per year, while 0.020 mg m^{-3} was the mean limit value for the calendar year.

Among basaltic volcanoes, Mt Etna (Italy; Fig. 1) has proved to be a great producer of ash in ~~the last 20 years~~~~decades and more~~ recent decades. S~~Indeed, s~~ince 1989, Etna has undergone recurrent explosive activity consisting of more than 200 paroxysmal episodes, and two main long-lasting explosive eruptions in 2001 (Taddeucci et al., 2002; Scollo et al., 2007) and 2002-03 (Andronico et al., ~~2005~~2009a and reference therein) that produced prolonged ash emissions ~~(Taddeucci et al., 2002; Andronico et al., 2008, 2009)~~. Paroxysmal events are characterised by explosive activity ranging in style from Strombolian to lava fountains, often as sequences of episodes within periods of weeks to months at the summit craters (Branca and Del Carlo, 2005). Recently, these paroxysmal sequences have been considered single "episodic" eruptions by Andronico and Corsaro (2011). Most of these paroxysms are typically associated with the production of ~~ash~~ tephra (from ash to

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lapilli to bombs) injected into the atmosphere and dispersed all around the volcano and further, where they may cause light to relatively heavy and serious fallout. In urbanised areas, in fact, paroxysms characterised by low mass eruption rate (i.e. values of ~2×10^{2} kg s^{-1}; 16 November 2006; Andronico et al., 2009b) have produced deposits prevalently made of ash, while paroxysms with high mass eruption rate (i.e. $4.5 \pm 3.6 \times 10^{5}$ kg s^{-1}; 23 November 2013; Andronico et al., 2015) have produced lapilli fallout deposits, differing also from a hazard point of view.

The health effects from particulate matter in the Etnean area have been conducted by Fano et al. (2005), who compared the levels of PM_{10} in the cities of Catania and Acireale (Fig. 1) during the intense fallout from the 2002-03 eruption with PM_{10} values measured in the same season but during years without volcanic activity. These Authors concluded that, although a significant increase of PM_{10} in the air was recorded for several days that greatly exceeded the threshold fixed by law at that time (0.050 mg m^{-3} over 24 hours), there was no evident direct cause of respiratory diseases from the ash fallout. They did note a temporary increase in cardiovascular diseases, particularly among the elderly, which however they assumed to be related uniquely to the stress caused by the eruption. Such effects on the cardiovascular system have also been documented in non-volcanic areas (WHO Air Quality Guidelines Global, 2006; Delfino et al., 2005). However, a retrospective study by Lombardo et al. (2013) reports, contrary to the results by Fano et al. (2005), on an increase in hospital admissions for cardiovascular morbidity along with a decrease in the rate of admission for respiratory diseases, finding a significantly higher frequency of visits to the emergency department for acute respiratory and cardiovascular diseases, and ocular disturbances during the ash exposure time period in the three main hospitals of Catania in 2002, as compared to the same period of the previous year. Furthermore, Barsotti et al. (2010) simulated the concentration of 10-μm volcanic particles (both in the air and on the ground) in several towns and key infrastructure around the volcano, showing that the re-mobilization of ash may considerably increase the concentration of the study-class of particles in the air.

In this work, we quantitatively evaluate the effects of ash fallout on the air quality during explosive activity from Etna, namely the 2011-12 and 2013 episodic eruptions (25 and 21 paroxysmal episodes, respectively; Andronico et al., 2014b) from the New-South East Crater (Fig. 1). The problem for human health is potentially considerable because approximately 900,000 people~~inhabitants~~ live on the slopes of Etna, Catania being the largest city with 300,000 inhabitants and comprising another twelve towns each of which numbers more than 20,000.

To this end, we carried out short-duration PM_{10} surveys of particulate matter in the air at three sites with different environmental conditions: i) within a few hours after ash fallout following the 15 November 2011 lava fountain, and ii) in similar weather conditions but without any evident air

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pollution by volcanic ash. Sedimentologic, ~~morphoscophic~~ morphological and petro-chemical analyses were performed on ash samples collected at the measurement sites, in order to determine the grain-size, componentry, shape and composition of particles. Furthermore, we discuss the potential risk caused by tephra fallout in the Etnean urban areas, suggesting simple measures to prevent and mitigate such effects.

2 The 15 November 2011 lava fountain episode

On 11 January 2011, the South-East Crater (SEC; Fig. 1) resumed its eruptive activity that gave rise to a lava fountain episode in the night between 12 and 13 January 2011, ~~being~~ the first of a sequence of 25 events over the next months. The intense activity gradually built up a new cone on the east flank of SEC, named New South-East Crater (hereafter NSEC; Fig. 1; Andronico et al., 2014a, b; Behncke et al., 2014).

The 15 November 2011 episode studied here was the 18th and occurred in partially cloudy conditions around the volcano which prevented full visibility of the eruptive phenomena, in particular of the eruption column. The eruptive activity resumed in the morning around 5:45 GMT (local time: GMT+1). A thermal anomaly was observed by video-recordings from the network of cameras managed by Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania-Osservatorio Etneo (INGV-OE). The anomaly, located on the eruptive fissure cutting the new cone, heralded the downward advancement of a lava flow that was evident since 6:05 GMT, while discontinuous, low explosions became~~gan to be~~ visible from the upper vent within the new cone after 8:20 GMT (*resumption phase* of Alparone et al., 2003; Fig. ~~3a~~2a). The Strombolian explosions slowly increased in frequency and intensity, extending also along the eruptive fissure, until to about 11:15 GMT, when they began to produce almost continuous magma jets up to at least 300 m high (Fig. ~~3b~~2b), forming (since 11:30 GMT) an eruption column up to several km above the volcano (*paroxysmal phase*; Fig. ~~3c~~2c). This activity lasted with similar intensity and features for more than 1 hour; after 12:20 GMT, the lava fountains dramatically dropped in intensity and in a few minutes the activity passed to lower-intensity Strombolian explosions (*conclusive phase*; Fig. ~~3d~~2d); also the eruption column, no longer fed, became exhausted in a few minutes. All the effusive and explosive phenomena ceased completely after 13:00 GMT.

The eruption column was driven eastward by winds blowing above the volcano, causing tephra fallout on the east flank of Etna and further towards the coastline and over the Ionian Sea (Fig. 1).

3 Methods

3.1 DustTrak measurements

PM_{10} measurements were carried out by a TSI® DustTrak™ (hereafter DT) aerosol monitor (Model 8520), a portable laser photometer providing real-time digital readout of airborne particulates (Fig. ~~2a~~3a). In volcanology, the DT was extensively used in the Caribbean island of Montserrat to evaluate the impact of the ash erupted by the Soufriere Hills Volcano between 1996 and 1999 and particularly the exposure of islanders to respiratory hazards (Moore et al., 2002; Searl et al., 2002). These Authors produced guidelines for air quality surveys in volcanic areas characterized by ash fallout in urban settlements. Moore et al. (2002), in particular, provided two strategies for investigating PM_{10} levels in Montserrat: a network of static test sites by which to carry out continuous monitoring and short-duration tests, ranging between 15 min and one hour. In both cases they set the DT for 1-minute average recording.

In this work, we measured PM_{10} concentration in the air at three different sites a few hours after the 15 November 2011 lava fountain. The sites were selected on the eastern flank of the volcano in some inhabited areas affected by the ash fallout (Fig. 1). Short-duration tests were done during the mapping and sampling of the tephra fallout performed soon after the eruption to prevent the removal of the original amount of tephra on the ground.

Site 1 is on the SS114 road linking Acireale with Catania at 21.3 km from the eruptive vent, *site 2* is about 1.5 km north on the same road and 20.4 km from NSEC, while *site 3* is on the SP148 within the Fleri village, 12.8 km from NSEC. These sites were selected on the basis of their different features in terms of road traffic. *Site 1* is on a road with “average” but continuous, fairly smooth flowing (both cars and lorries) traffic. Measurements were carried out at the road side at about 1 m of height. *Site 2* is at a main crossroads where cars must stop at the traffic lights. There is more traffic here than at site 1, and the DT operated at 80 cm of height just below a traffic light pole. *Site 3*, finally, is located on a road with regular traffic flow crossed by a secondary, quiet to busy road with a stop sign. The DT measured at 40 cm of height. The traffic at this site is roughly intermediate between site 1 and site 2. All the measurements were carried out at the same 1 m horizontal distance from the carriageway.

We measured PM_{10} over 10- to 16-minute periods; the DT was set with a time constant of 10 s, i.e. the display showed readings averaged over the previous 10 s, while the frequency/averaging period was fixed to 1 min, i.e. readings were recorded at 1-minute intervals. We observed that just a few hours after the tephra fallout ash was swept laterally by the cars causing remobilization phenomena and accumulation at both sides of the carriageway (Fig. ~~2b~~3b).

We repeated measurements a month later, on 15 December 2011, at the same time and with the same instrument set up and similar weather conditions.

The methodology used does not entirely follow the exposure guidelines for PM_{10} specifically for volcanic environments. Our focus was primarily on measuring the increase in PM_{10} concentrations during and immediately after tephra fallout. In the future, we plan to undertake more detailed surveys with more attention to a precise procedure. The instrument should be set up at a standard level in all the sites to facilitate comparisons, and the DustTrak set at an appropriate height for human exposure, e.g. 1.5 m, which is considered the 'breathing zone' for adults. The duration of measurements should be in 24 hour periods for comparison with EU standards. In the future, it might also be helpful to measure the PM_{10} at different heights at the same site to quantify a vertical gradient, thus evaluating if there is any variation in PM_{10} concentration with height.

3.2 Sample analyses

A tephra sample (NSEC1~~PM1~~, NSEC~~PM~~2 and ~~PM~~NSEC3) for each site was collected on a measured surface to evaluate the ~~weight~~ mass for m^2. ~~PM~~NSEC2 and ~~PM~~NSEC3 samples were selected for textural investigation and morphological observation since ~~PM~~NSEC1 was collected very close to ~~PM~~NSEC2. At the Laboratory of Sedimentology, INGV-OE, we carried out grain-size analysis by CAMSIZER (Lo Castro and Andronico, 2008) at 1/2-ϕ ~~phi~~ intervals (ϕ being the $-\log_2 d$, where d is the particle diameter in mm), estimating the percentages of different size classes in volume %~~)~~ and ash componentry characterization under binocular microscope (Nikon SMZ1500). At Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa Laboratory, we performed ~~morphoscopical~~ morphological analyses of clasts and chemical analyses of glass and minerals using a scanning electron microscope Zeiss EVO MA 10 equipped with an Oxford ISIS microanalytical system.

4 Results

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The mass per square meter of the samples is significantly different from *sites 1* and *2* with respect to *site 3*. In the most distal and lateral sample (~~PM~~NSEC1), the weight amounted to ~490 g m^2, a value fairly similar to the close sample ~~PM~~NSEC2 (~440 g m^2), while ~~PM~~NSEC3 was ~1500 g m^2.

4.1 DustTrak measurements

On 15 November, we measured PM_{10} particulate matter between 2 hours (*site 1*) and 5 hours (*site 3*) after the end of the lava fountain. All the loggings show a few peaks in the pattern (Fig. 4a-c, blue lines), indicating the significant influence of passing vehicles as observed during the readings. At *site 1*, the least affected by car traffic, we recorded an average of 0.084 mg m^{-3}, with maximum value of 0.125 mg m^{-3}. At *site 2*, the average value is considerably higher (0.642 mg m^{-3}) and the same is for the maximum value (1.285 mg m^{-3}). Remarkably, the minimum value recorded is 0.337 mg m^{-3}, far higher than the maximum value recorded at *site 1*. Finally, at *site 3* all the statistic values are very high: average at 0.935 mg m^{-3}, minimum at 0.379 mg m^{-3} and maximum at 1.755 mg m^{-3}.

Measurements carried out at the same sites a month later gave surprisingly ~~very~~ low values of PM_{10} (Fig. 4a-c, red lines). *Site 1* confirmed the lowest values of particulate matter: average of 0.033 mg m^{-3}, minimum of 0.023 mg m^{-3} and maximum of 0.045 mg m^{-3}. These values show a very limited variability between these three statistic values. At *site 2* the differential among the statistics is increased though not significantly: average 0.060 mg m^{-3}, minimum 0.026 mg m^{-3} and maximum 0.149 mg m^{-3}. *Site 3*, finally, was again the site with the highest PM_{10} values, with an average of 0.081 mg m^{-3}, a minimum of 0.061 mg m^{-3} and a maximum of 0.192 mg m^{-3}.

4.2 Grain-size, textural and petro-chemical data

The grain-size distribution of ~~PM~~NSEC2 and ~~PM~~NSEC3 samples shows both a Gaussian pattern peaked on 1 mm and 2 mm, respectively (Fig. 4d). The most proximal sample (~~PM~~NSEC3) is obviously coarser, with only 17 % of the collected tephra <1 mm, with respect to the distal sample (~~PM~~NSEC2) which amounts to a good deal more than 60 % of particles below the same size of 1 mm. It should be noted that very fine ash particles (less than 0.125 mm) are practically absent in the proximal sample (just 0.1 % of clasts in the range 0.09-0.125 mm), while we measured a higher, even if poorly significant value of 0.9 % between 0.045 mm and 0.125 mm in sample ~~PM~~NSEC2. ~~PM~~NSEC2 and ~~PM~~NSEC3 samples are both mainly made up of basaltic sideromelane clasts (ca. 90 %) consisting of light brown, fresh, vesicular clasts with irregular to subrounded shape and smoothed surface (Figs. 5 and 6). The rest of the sample is formed of black, poorly vesicular, blocky clasts (tachylite), rare lithic particles (reworked lavas and scorias) and loose crystals (plagioclase).

SEM analyses of ash indicate that clasts are from highly to moderately vesicular, with elongated or blocky shapes (Fig. 6a-c). Clasts show smoothed surfaces and delicate edges. The finer fraction of the deposit (Fig. 6d) is formed mainly by fragments of larger clasts with similar features. Furthermore, shape parameters obtained by CAMSIZER analyses for NSEC2 and NSEC3 samples give aspect ratio of 0.69 and 0.70, and sphericity of 0.71 and 0.78, respectively, indicating on average particles are moderately elongated and sub-rounded. These morphological characteristics are typical of most of the lava fountain products.

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Bulk rock composition of scorias is K-trachybasaltic like the other recent volcanics of Etna (Viccaro et al., 2015). Ash samples are poorly porphyritic with phenocrysts of plagioclase and clinopyroxene, and microphenocrysts of olivine and oxides (titaniferous-magnetite). The groundmass is glassy with large abundance of microlites of plagioclase, clinopyroxene, olivine and oxides (Fig. 7). Composition of glass is more evolved and alkali-rich as we can observe in the Total Alkali Silica diagram (Fig. 8 and Table 1), where the 15 November 2011 samples plot between the basaltic-trachyandesite and the phono-tephrite fields.

5 Discussion

5.1~~2~~ The 15 November 2011 PM$_{10}$ ~~pilot~~ test

~~In good agreement with the latter research, our study shows that the presence of fine-grained tephra in~~ on ~~the ground may be highly hazardous in terms of PM$_{10}$ concentrations in the air when not quickly removed. Sites usually characterised by low PM$_{10}$ values proved to be very sensitive after the fallout from lava fountains, because relatively low quantities of tephra deposit per square meter (from ~500 g m^{-2} to >1500 g m^{-2}) were able to produce significant concentrations of particulate matter in the air.~~

Measurements carried out ~~a month after the~~ shortly after the 15 November 2011 Etna lava fountain have shown that the values of PM$_{10}$ are ~~significantly different~~higher than those measured ~~on 15 November 2011,~~ a month after at the same sites. ~~documenting~~ This survey has documented that tephra fallouts on the ground ~~from Etna~~ may ~~significantly~~ pollute the air quality, with PM$_{10}$ levels (at least during the short-duration tests) far exceeding the recommended limit for a 24 hour exposure. In particular, PM_{10} values are higher though within the same order of magnitude in *site 1*, the location least affected by vehicular traffic. Conversely, *site 2* and *3* are both characterised by average, maximum and minimum values of PM_{10} 6-13 times higher a few hours after the 15 November lava fountain. Interestingly, *sites 1* and *2*, though affected by similar amounts of tephra, show substantial differences in the production of finer particles and this may be related to the varying intensity of vehicular traffic, higher at *site 2* with respect to *site 1*. Further, Figure 4 highlights that the 1-min, see-saw averaged line is heavily dependent on the vehicular flow, which by disturbing the tephra deposit is able to raise a clearly visible, irritating cloud of fine particles including a high percentage of PM_{10}.

Given that the local authorities in charge of the territory should take these data into consideration, we think they should reflect especially on: 1) the average PM_{10} value recorded during our tests, which remains well over the 24~~-H~~ h limit (0.050 mg m^{-3}) fixed by law at all three sites, i.e. only twice at *site 1* but 13 and 19 times at *sites 2* and *3*, respectively, and 2) the minimum values, which, though not so high as at *site 1* (0.49 mg m^{-3}), reached very high readings at *sites 2* and *3* (0.337 mg m^{-3} and 0.379 mg m^{-3}, respectively), i.e. ~7 times the limit fixed to safeguard human health over periods of 24 hours. Sites usually characterised by low PM_{10} values proved very sensitive after the fallout from lava fountains, because relatively low quantities of tephra deposit per square meter (from ~500 g m^{-2} to >1500 g m^{-2}) were able to produce significant concentrations of particulate matter in the air.

The ~~study~~ grain-size distributions of collected tephra show that ~~their grain-size is~~ 99.8 % ~~(PM3)~~ and 94.8 % ~~(PM2) higher~~ of the volume for samples NSEC3 and NSEC2 (respectively) is coarser than 1 mm, and all the samples ~~the total percentage higher~~are composed of particles coarser than 10 µm~~micron~~. Hence, we infer that the air contamination by PM_{10} is not due to the direct ash fallout but to the breakup of the coarser clasts after mechanical pressure from vehicular transit. The breakage could be enhanced to the fragility of the sideromelane particles, which represent ca. 90 % of the samples as morphological and component analyses indicate.

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5.2 Quantitative estimation of the tephra grinding by car passage

The passage of the cars on the roads covered by tephra fallout causes the grinding of the original tephra on the ground itself and its accumulation along the edge of the carriageway (Fig. 3b). This simple as well as reiterated observation suggested we evaluate the phenomenon quantitatively to understand if the original grain-size of the tephra on the ground could be significantly modified.

We tested this observation following the lava fountain at SEC on 23-24 November 2007 (Andronico et al., 2007). The paroxysmal episode produced tephra fallout more than 80 km NE away from Etna, reaching the Calabria region. At 14 km from the vent along the dispersal axis (Solicchiata village), we collected two distinct samples, one unaltered (~1,120 g/m^2) and another one from the edge of the carriageway, clearly related to the passage of the cars which had ground down and accumulated a macroscopically finer deposit.

The comparison between the grain-size distribution of the two samples (Fig. 9) shows that the mode of the "ground" sample is at least one-phi shifted toward finer classes with respect to the original deposit (from 1.4-2 mm to 0.71-1 mm). What is more striking, however, is that while the grain-size distribution of the original sample indicates that only 1.6 % was lower than 1 mm, the "ground" sample was formed by more than 60 % of particles with dimensions <1 mm. Further, to better quantify the finer particles, the fraction <2 mm (i.e., 96.8 % of the total sample) was analyzed using the CILAS laser diffraction analyzer (http://www.cilas.com/granulometrie.html) at University of Geneva; the cumulative grain-size distribution curve shows that it contains 2.8 % of particles with dimension of <8 µm. In other terms, for each 100 g m^{-2} the grinding produced ~2.5 g m^{-2} of PM_{10} particles in the ground deposit. This is indeed a high percentage of potentially dangerous particles for human exposure directly produced by passing cars.

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5.3 Tephra fallout in urban settlements

In the past, high PM_{10} values have been measured by the network of air monitoring stations located in the city of Catania, which have exceeded the EU set threshold even up to some tens of times greater after long-lasting fallout (2002-03 eruption; Rete di monitoraggio ambientale, 2002) or single paroxysmal events (e.g., July 2011). These data, easily accessible at the web-page maintained by the Environmental Pollution Office of the municipality of Catania, confirm our warning on the potential effects of tephra fallout in the Etna region.

These results are also supported by measurements taken on 6 October 2011 in Ragalna town (Fig. 1), 8 days after the tephra fallout on 28 September 2011 during the lava fountain episode. Here, the tephra cover (96 % of which made up of 0.25-1 mm sized particles) had not been completely swept away from the streets, reaching significant thicknesses (up to several centimetres) in specific points. Also in this case, we measured high PM_{10} peaks up to 0.300 mg m^{-3} correlated with the transit of cars over the ash mounds. In other terms, as occurred during our measurements following the 15 November 2011 lava fountain, the grinding by the car passage was able (a week after the end of the tephra fallout) to cause the remobilization of volcanic particulate matter and its resuspension in the air, the effects of which have been quantified by the high PM_{10} concentrations measured by DustTrak.

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Recently, the villages of Zafferana Etnea and Piedimonte Etneo, located 10 km eastward and 17 km north-eastward of the NSEC, were covered by unusually thick tephra fallout deposits (2-3 cm depth) produced by high-energy lava fountain events. These cumulated >7000 g m^{-2} at Zafferana on 16 March 2013, and ~6000 g m^{-2} at Piedimonte on 23 November 2013, respectively (Lo Castro et al., 2013; Andronico et al., ~~2013~~2015), causing a few days of temporary closure of traffic. Notably, both during the removal of the accumulated tephra and the remobilization by car traffic, a high re-suspension of ash affected the roads causing the formation of a PM_{10} ~~ash~~cloud, thus increasing the ash ~~-~~exposure and inevitable inhalation for several days (Fig. ~~9~~10).

This is also demonstrated by Thorsteinsson et al. (2012), who reported that ash resuspension near the ground was able to generate levels of particulate matter similar to those caused by direct tephra fallout during the 2010 Eyjafjallajökull eruption in Iceland. The wind erosion due to strong storm episodes remobilized the ash deposited during this eruption, generating resuspension events with higher concentration of PM_{10} also several tens of km away from the deposit (Leadbetter et al., 2012; Arnalds et al., 2013). Furthermore, the sweeping of tephra from the road several days after the fallout had also increased the resuspension effects (Leadbetter et al., 2012).

Studies by Hincks et al. (2006) and Barsotti et al. (2010) also linked the resuspension to the amount of tephra cover and showed the direct correlation between the thickness of tephra deposit to the higher concentrations of PM_{10} and 10-µm volcanic particles, respectively.

Finally, it should be remembered that physicochemical analyses carried out on ash samples from the 2002-03 Etna eruption also showed that fine ash particles may generate hydroxyl radicals, an additional source of respiratory toxicity (Horwell et al., 2007), thus increasing the potential health hazard.

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6 Conclusions

Tephra fallouts are a source of particulate matter in the air and their high frequency in the east sector of Etna may maintain high levels of PM_{10} for several days in the urban settlements around the volcano. Our study, in particular, suggests that the presence of fine-grained tephra on the ground may be hazardous in terms of PM_{10} concentrations in the air when not quickly removed, and matches well with a medical study on acute health effects due to volcanic ash exposure during the 2002 Etna eruption.

~~We are aware that the methodology adopted does not entirely follow the EU legislation for urban areas and also exposure guidelines for PM_{10} specifically for volcanic environments.~~ Although our measurements represent preliminary short-duration tests to evaluate eventual~~the~~ exposure~~ of the community~~ to volcanic ash at Etna, they may nonetheless represent a starting point for future researches. Data showed that after the 15 November 2011 lava fountain, the PM_{10} concentrations exceeded the EU limit of 0.050 mg m^{-3} (fixed over 24 hours) 91 %, 90 % and 94 % of the time in the three investigated sites.

Our tests urge the ~~adequate~~ planning of a systematic~~suitablethe~~ monitoring ~~survey~~of the PM_{10} concentrations ~~–~~especially after tephra fallout from paroxysmal activity. ~~and the~~ Measuring and assessing the real levels of exposure needs to be done to understand eventual respiratory (and cardiovascular) hazards to the Etnean population~~ during, but above all, after tephra fallout from paroxysmal activity~~ .

It is noteworthy that all the sites selected for our PM_{10} measurements (*sites 1*, *2*, *3* and Ragalna) are not located in highly urbanised areas in terms of people passing (whether walking, cycling, motorbiking or driving), so that the risks and thus the effects on the human health could be significantly higher in the town centres. Here, the continuous vehicular traffic could lead, on one hand, to the formation of a quasi-permanent PM_{10} cloud within the first 2-3 m of height above the ground, and on the other, to a continuous and marked exceeding of the PM_{10} limits set to protect human health.

We conclude by hoping that the impact from ash fallout in the Etnean territory~~ and surroundings~~ will not be underestimated but given due attention to avoid potential health risks~~ diseases from volcanic particulate matter~~. Although difficult, if not impossible, to prevent exposure to high concentrations of PM_{10} entirely, this goal might be achieved by carrying out simple but effective actions and precautions; first and foremost, the swift and effective removal of the ash deposit in the urbanized areas and public roadways within a few hours from the tephra deposition on the ground, limiting the re-suspension of high amounts of particulate matter into the air as well the grinding of tephra by passing cars.

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Figure captions

Figure 1 - Digital elevation map of Mt Etna showing the sites (full yellow circles) chosen for PM_{10} measurements and the collected samples (SITE 1, SITE 2 and SITE 3). The broken yellow line shows the extent of tephra fallout from the 15 November 2011 lava fountain. Blue areas represent the main cities in this volcano sector, especially those reported in the text. Right-top inset: location of Sicily. Left-bottom inset: map of the summit craters *(white rectangular represented in a)* on September 2011 (courtesy of INGV — Cartography Laboratory): NEC Northeast Crater, VOR Voragine, BN-1 and BN-2 Bocca Nuova pit-craters, SEC Southeast Crater, NSEC New Southeast Crater.

~~Figure 2 - PM_{10} measurement carried out on 15 November 2011 in Acireale at site 2 (SS114 road): a) DustTrak working; the display shows the averaged reading over the previous 10 s; b) transit of cars at the crossing.~~

Figure ~~3~~ 2 - Images extracted from the INGV-OE video-camera recordings of La Montagnola site (a, b, d: thermal camera; c: true-colour camera) showing the main phases of the 15 November 2011 lava fountain at the new cone of SEC: a) the beginning of the explosive and effusive activity in the upper vent and eruptive fissure of the new cone, respectively; b) lava fountains from the eruptive fissure; c) the eruption column formed above; d) the last explosions before the cessation of each eruptive phenomena.

Figure 3 - PM_{10} measurement carried out on 15 November 2011 in Acireale at site 2 (SS114 road): a) DustTrak working; the display shows the averaged reading over the previous 10 s; b) transit of cars at the crossing.

Figure 4 – a, b, c) Plots showing PM_{10} measurements in three studied sites: a) site 1, Aloha Hotel ~~Aloha~~; b) site 2, Acireale; c) site 3, Fleri. The time interval of the number measurements is 1 min. Blue lines and diamonds: values measured in the afternoon of 15 November 2011, a few hours after the tephra fallout; red lines and squares: values measured on 15 December 2011, in absence of volcanic event. At the side of each plot are reported the main PM_{10} statistics data: Ave= average value; Max= maximum value; Min= minimum value. d) Grain-size histograms concerning samples ~~PM~~NSEC2 and ~~PM~~NSEC3.

Figure 5 - Binocular microscope images showing different morphological types of ash particles from ~~PM~~NSEC2 (a, b) and ~~PM~~NSEC3 (c) samples.

Figure 6 - Scanning electron microscope secondary electrons (SEM-SE) images representative of the textures identified in studied tephra showing moderately vesicular, glassy scoriaceous fragments with fluidal texture (sideromelane) and scarce poorly vesicular, blocky clasts (tachylite). a and b) ~~PM~~NSEC~~1~~3 sample at Fleri; c and d) ~~PM~~NSEC2 sample at Acireale.

Figure 7 – Scanning electron microscope secondary electrons (SEM-BSD) images representative of textures identified in the 15 November 2015 ash; pl: plagioclase; ol: olivine.

Figure 8 – Total alkali-silica classification diagram of Le Bas et al.~~,~~ (1986).

Figure 9 – Comparison between the grain-size distribution of two samples collected at the same site in Solicchiata village (14 km northeast from the vent): a) primary and b) reworked tephra fallout deposit after grinding by passing cars.

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Figure 9 10 – The remobilization of ash in the air after the 16 March 2013 tephra fallout at Zafferana Etnea.

Table Caption

Table 1 - SEM-EDS analyses of major elements in glass of 15 November 2011 ash fragments (wt.% average value); # number of analyses; STD: standard deviation value.