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Ash fallout scenarios at Vesuvius: Numerical simulations and implications for hazard assessment

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ABSTRACT

Volcanic ash fallout subsequent to a possible renewal of the Vesuvius activity represents a serious threat to the highly urbanized area around the volcano. In order to assess the relative hazard we consider three different possible scenarios such as those following Plinian, Sub-Plinian, and violent Strombolian eruptions. Reference eruptions for each scenario are similar to the 79 AD (Pompeii), the 1631 AD (or 472 AD) and the 1944 AD Vesuvius events, respectively. Fallout deposits for the first two scenarios are modeled using HAZMAP, a model based on a semi-analytical solution of the 2D advection–diffusion–sedimentation equation. In contrast, fallout following a violent Strombolian event is modeled by means of FALL3D, a numerical model based on the solution of the full 3D advection–diffusion–sedimentation equation which is valid also within the atmospheric boundary layer. Inputs for models are total erupted mass, eruption column height, bulk grain-size, bulk component distribution, and a statistical set of wind profiles obtained by the NCEP/NCAR re-analysis. We computed ground load probability maps for different ash loadings. In the case of a Sub-Plinian scenario, the most representative tephra loading maps in 16 cardinal directions were also calculated. The probability maps obtained for the different scenarios are aimed to give support to the risk mitigation strategies.

1. Introduction

Volcanic ash fallout constitutes a serious hazards to communities settled around active explosive volcanoes. The assessment of such hazards are, consequently, a matter of importance for public safety in volcanic regions like the highly urbanized area around Vesuvius, inhabited by millions of people. Hazards associated with a possible renewal of explosive activity at Vesuvius have been a subject of several studies (e.g., Barberi et al., 1990; Macedonio et al., 1990; Cioni et al., 2003). However, all previous studies assessed hazards for a Sub-Plinian scenario only and did not consider other higher and lower magnitude events. The most severe ash fallout hazard associated with Plinian and Sub-Plinian eruptions, further subdivided in Sub-Plinian I and Sub-Plinian II by Cioni et al. (2008-this issue), is due to the collapse of roofs because of ash loading that potentially involves areas up to few hundreds of km^2. Effects and damage associated with a violent Strombolian eruption are less severe from those of a Plinian or a Sub-Plinian scenario. However, several eruptive episodes at Etna and other volcanoes (*e.g.*, 1944 AD Vesuvius) have shown that eruptions of lower magnitude can also create serious problems to local communities, especially in very urbanized areas (such as the Neapolitan area). Beside possible roof collapses by ash loading in limited areas close to the volcano, volcanic ash can also cause, even for minor events, severe disruption of transportation systems due to loss of visibility, disruption to communications due to interference to radio waves or direct damage to communications, temporary shut down of airports and aerial corridors, partial or total destruction of agricultural crops and damage to forestry, irritation of eyes and skin and potential respiratory symptoms produced by ash inhalation. Our goal here is to investigate ash fallout in the Vesuvius area for three different scenarios representative of a Plinian, a Sub-Plinian I, and a violent Strombolian eruptions respectively using as a reference well-documented eruptions such as those occurred in 79 AD, 1631 AD, 472 AD, and 1944 AD.

The Sub-Plinian II category, characterized by a lower intensity and Magnitude than Sub-Plinian I (Cioni et al., 2008), was not investigated in the present study.

Among the Plininan eruptions, the 79 AD Vesuvius eruption is surely one of the most extensively studied eruptions ever. It is famous for the destruction of the Roman towns of Pompeii and Herculaneum and for the detailed chronicles written by the Roman lawyer Pliny the

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Younger who described the events in which his uncle, Pliny the Elder, died. The volcanological aspects of the 79 AD eruption have been described by numerous authors (e.g. Lirer et al., 1973; Santacroce, 1983; Sigurdsson et al., 1985; Carey and Sigurdsson, 1987; Santacroce, 1987; Lirer et al., 1993; Scandone et al., 1993). The eruption comprised several phases. The graded Plinian fallout deposit associated with the purely magmatic phase, with a high sustained eruption column between 15 and 26 km (Carey and Sigurdsson, 1987), shows a lower layer of white phonolitic pumice ("White pumice") overlaid by an upper layer of tephritic-phonolitic pumice ("Gray pumice"). This eruptive phase ended with the collapse of the eruptive column and the subsequent emplacement of pyroclastic flows.

Two Sub-Plinian I eruptions are considered here (those occurred in 1631 and 472 AD). The eruption occurred in 1631 AD started on 16 December 1631 and produced a sustained column for about 8 h with an average height of 16 km, whereas the eruption occurred in 472 AD, also known as the "Pollena" eruption (Santacroce, 1983; Rosi and Santacroce, 1983; Mastrolorenzo et al., 2002; Principe et al., 2004; Rolandi et al., 2004; Cioni et al., 2008-this issue), produces a sustained column between 12 and 20 km.

Finally, the violent Strombolian eruption occurred in 1944 AD and was the last eruptive event that occurred at Vesuvius. The eruptive phase started with a sequence of lava flows followed by fire-fountaining episodes which evolved into a convecting eruptive column sustained for few days ending up with a phase of Vulcanian explosions (Imbò, 1949) with maximum column height of 5 km.

For each scenario we computed ground ash load probability maps which can provide potential decision-support to the hazard assessment for future eruptions at Vesuvius.

2. Models for volcanic ash transport and fallout

The ash fallout models we apply consider only the transport and deposition of lapilli and coarse ash, i.e., tephra particles from few mms to several microns in diameter (from $\Phi\simeq-5$ to $\Phi\simeq4$). Beyond a certain distance from the eruption column, the dispersion and sedimentation of tephra is governed mainly by wind transport, turbulent diffusion, and settling of particles by gravity (Armienti et al., 1988; Macedonio et al., 1988). Particles with a similar dynamic regime are commonly grouped into families or classes which, in general, can have interactions among them. Aggregation of finer particles during their fall (e.g. Cornell et al., 1983) is the most obvious evidence for particle interaction. However, if the concentration of particles is sufficiently dilute one can neglect interaction among particles belonging to different classes. Under this hypothesis the concentration of particles of class j is described through the mass conservation equation as (Costa et al., 2006):

$$\frac{\partial C_j}{\partial t}+U_X\frac{\partial C_j}{\partial X}+U_Y\frac{\partial C_j}{\partial Y}+(U_Z-V_{sj})\frac{\partial C_j}{\partial Z}=-C_j\nabla\cdot U+C_j\frac{\partial V_{sj}}{\partial Z}$$
$$\frac{\partial}{\partial X}\left(\rho K_X\frac{\partial C_j/\rho}{\partial X}\right)+\frac{\partial}{\partial Y}\left(\rho K_Y\frac{\partial C_j/\rho}{\partial Y}\right)+\frac{\partial}{\partial Z}\left(\rho K_Z\frac{\partial C_j/\rho}{\partial Z}\right)+S_j \quad (1)$$

where C_j denotes concentration of particle class j, t is time, (U_X,U_Y,U_Z) are the components of the wind velocity vector, K_X,K_Y and K_Z are the turbulent diffusion coefficients (diagonal terms of the turbulent diffusion tensor), ρ is the atmospheric density, and V_{sj} and S_j stand, respectively, for the terminal settling velocity and source term for class j. The advection–diffusion–sedimentation (ADS) Eq. (1), is of general applicability and must be solved numerically. However, under certain additional hypothesis, it can be simplified to derive analytical or semi-analytical solutions.

2.1. A model for high eruptive column: Plinian and Sub-Plinian scenarios

For large eruptive columns most of the ash transport process occurs outside the Atmospheric Boundary Layer (ABL). Consequently, in a first-order approach, it can be assumed that the vertical diffusion component is negligible with respect to the horizontal ones and that the terrain effects and the vertical wind component become a second-order effect. In addition, if one assumes also that the horizontal wind components are constant in time and uniform along the horizontal domain, Eq. (1) simplifies to:

$$\frac{\partial C_j}{\partial t}+U_x\frac{\partial C_j}{\partial x}+U_y\frac{\partial C_j}{\partial y}-\frac{\partial V_{sj}C_j}{\partial z}=K_x\frac{\partial^2 C_j}{\partial x^2}+K_y\frac{\partial^2 C_j}{\partial y^2}+S_j. \quad (2)$$

The model HAZMAP (Macedonio et al., 2005) we used for the simulations is based on a semi-analytical solution of the simplified Eq. (2). Dividing the vertical computational domain into N_{layer} layers in which settling and wind velocity are assumed constant, the total mass on the ground M_G can be computed as the sum of the contributions from each of the point sources distributed above the vent and from each particle settling velocity class:

$$M_G(x,y)=\sum_{j=1}^{N_{v_s}}\sum_{i=1}^{N_{\mathrm{sources}}}\frac{M_i f_j}{2\pi\sigma_{Gi}^2}\exp\left[-\frac{(x-x_{Gi})^2+(y-y_{Gi})^2}{2\sigma_{Gi}^2}\right] \quad (3)$$

where $\vec{x_{Gi}}=\vec{x_{0i}}+\sum_k\vec{U_k}\Delta t_k$ and $\sigma_{Gi}^2=2K\Sigma_k\Delta t_k$ are the center and the variance of the Gaussian respectively ($\Delta t_k=(z_k-z_{k-1})/v_{s,k}$ is the time for a particle to cross the layer k), N_{sources} indicates the number of source points, N_{v_s} is the total number of settling velocity classes, M_i is the total mass emitted from the point source in the layer i ($\Sigma_i M_i=M_{\mathrm{tot}}$, with M_{tot} total mass injected into the system), and f_j is the fraction of that mass belonging to the settling velocity class j ($\Sigma_j f_j=1$). In accord to Macedonio et al. (2005) and Pfeiffer et al. (2005), the source term for the Plinian and Sub-Plinian I eruptions was described using a modified parameterization proposed by Suzuki (1983).

2.2. A model for low eruptive column: the violent Strombolian scenario

For low eruptive columns (such the ones produced, for instance, during violent Strombolian events) most of the simplifying assumptions made to reduce Eqs. (1) to (2) are not longer valid because significant transport of ash occurs inside the ABL. In fact, wind fields and turbulent tensor components inside the ABL are much complex and terrain effects are, in general, not negligible. Moreover effects of bent-over on the plume due to the wind are not negligible. On the other hand, since winds in the lower part of the atmosphere vary rapidly in time and in space, there is a strong need to forecast the temporal evolution of both airborne ash concentration and ash deposit on the ground. It follows that simplified steady semi-analytical models like HAZMAP are not fully adequate in this context. For this reason we make use of the model FALL3D (Costa et al., 2006) to simulate ash fallout for the case of the violent Strombolian scenario. This model adopts realistic near surface wind fields that account for terrain effects, uses a realistic evaluation of the turbulent atmospheric diffusion based on the Monin–Obukhov similarity theory and a Large Eddy approach, and describe the source term using a model based on the Buoyant Plume Theory (BPT) as in Bursik (2001). For further details about the model see Costa et al. (2006). Obviously, Eq. (1) needs to be solved numerically and, in consequence, the model becomes less suitable to perform statistical studies and/or to solve inverse problems because the computational requirements become greater.

3. Ash fallout simulations and hazard maps

In this Section we describe the volcanological and meteorological data used for the analysis of ash fallout hazard from explosive eruptions at Vesuvius and we show the obtained hazard maps for the different scenarios.