

A computer model for volcanic ash fallout and assessment of subsequent hazard[☆]

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Abstract

HAZMAP is a FORTRAN code for the solution of the equations of diffusion, transport and sedimentation of small particles, in order to model the dispersion of ash generated by a convective column. The model was developed simplifying the advection–diffusion–sedimentation equation for volcanic ash transport in the atmosphere from three to two dimensions and using a semi-analytical computational method to greatly reduce the required computer time and memory. HAZMAP can be used either to simulate the mass distribution of the deposit if a wind profile is given (“deposit mode”), or to define the probability of a given accumulation of mass on the ground if a statistical set of wind profiles is provided (“probability mode”). The model needs the definition of the physical system (spatial distribution of the point sources, total erupted mass, settling velocity distribution, wind velocity profile, atmospheric turbulent diffusion coefficients), and of a computational grid. The output values of mass accumulation on the ground or the probability of mass accumulation are computed on a regular grid, suitable for further analysis.

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1. Introduction

HAZMAP is a computer program for simulating the diffusion, transport and sedimentation of volcanic particles in the atmosphere in two dimensions from discrete point sources. For example, when the point

sources are specified along a vertical line located above the volcano crater, the code is able to simulate the dispersion from a Planning column, and to obtain the mass distribution and settling velocity spectrum in the deposit. Input data are assigned in the file *hazmap.inp*, and output data are written in the *hazmap.out* file (probability mode) or in the *deposit.out* file (deposit mode). The program HAZMAP is written in standard FORTRAN 77 and typically runs on UNIX workstations and PCs.

2. Ash transport model

HAZMAP is based on a simple physical model which describes diffusion, transport and sedimentation of

[☆]Code is available from server at <http://www.iamg.org/CGEditor/index.htm>

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particles (ash and pumice) in two dimensions from one or more point sources. The dispersion of the particles in the atmosphere takes place under turbulent diffusion and wind transport (a reasonable assumption at large distances from the crater), whereas the fallout is controlled by the particle settling velocity, resulting from the action of gravity and the air drag. To create a fast zero-order computational model, several simplifying assumptions are made.

Far from the eruption column (e.g. few times the column height), the concentration C_j of particles with a given settling velocity $v_{s,j}$ can be described by a mass conservation equation:

$$\begin{aligned} \frac{\partial C_j}{\partial t} + w_x \frac{\partial C_j}{\partial x} + w_y \frac{\partial C_j}{\partial y} + w_z \frac{\partial C_j}{\partial z} - \frac{\partial v_{s,j} C_j}{\partial z} \\ = K_x \frac{\partial^2 C_j}{\partial x^2} + K_y \frac{\partial^2 C_j}{\partial y^2} + K_z \frac{\partial^2 C_j}{\partial z^2} + S \end{aligned} \quad (1)$$

where (x, y, z) are the spatial coordinates, t is the time, (w_x, w_y, w_z) are the wind velocity components, K_x , K_y and K_z are the diffusion coefficients (assumed to be constant), and S is a source function. Since the horizontal components of turbulence and wind are usually much greater than the vertical ones, the simplifying assumptions of negligible vertical wind w_z and diffusion coefficient K_z (Pasquill, 1974), (Armenti et al., 1988) were adopted. In this case, the atmospheric diffusion acts in the plane (x, y) ; and isotropic horizontal diffusion ($K_x = K_y = K$) is assumed.

The shape of the column, generally, is assumed to be:

$$\begin{aligned} S(x, y, z, t) \\ = \delta(t - t_0) \sum_k^{N_k} M_k \delta(x - x_v) \delta(y - y_v) \delta(z - z_k), \end{aligned} \quad (2)$$

where M_k represent the mass of particles emitted from the k th point source with coordinates (x_v, y_v, z_k) (x_v, y_v are the coordinates of the vent), N_k is the number of point sources considered and δ is the Dirac distribution.

The use of Eq. (2) is based on the assumption that all particles are emitted instantaneously (at $t = t_0$) from the point sources along a vertical line above the crater.

For a point source, (x_0, y_0, z_0) , in an infinite region, under conditions of uniform wind and constant settling velocity, the three-dimensional advection–diffusion–sedimentation equation:

$$\begin{aligned} \frac{\partial C_j}{\partial t} + w_x \frac{\partial C_j}{\partial x} + w_y \frac{\partial C_j}{\partial y} - v_{s,j} \frac{\partial C_j}{\partial z} \\ = K_x \frac{\partial^2 C_j}{\partial x^2} + K_y \frac{\partial^2 C_j}{\partial y^2} + K_z \frac{\partial^2 C_j}{\partial z^2} \end{aligned} \quad (3)$$

satisfies the exact analytical solution:

$$\begin{aligned} C(x, y, z, t) \\ = \frac{1}{4\pi K t} \exp \left[-\frac{(x - x_0 - w_x t)^2 + (y - y_0 - w_y t)^2}{4K t} \right] \\ \times \frac{1}{\sqrt{4\pi K t}} \exp \left[-\frac{(z - z_0 + v_{s,j} t)^2}{4K_z t} \right]. \end{aligned} \quad (4)$$

In the limit of $K_z \rightarrow 0$ Eq. (4) can be approximated by

$$\begin{aligned} C(x, y, z, t) \\ = \frac{1}{4\pi K t} \exp \left[-\frac{(x - x_0 - w_x t)^2 + (y - y_0 - w_y t)^2}{4K t} \right] \\ \times \delta(z - z_0 + v_{s,j} t). \end{aligned} \quad (5)$$

Eq. (5) describes the dispersion of particles in a horizontal plane (layer) which settles at velocity v_s . We divide the 3D computational domain into different horizontal layers in which Eq. (5) is valid. This allows us to treat the 3D dispersion of particles into the case of horizontally layered wind and negligible K_z as a 2D problem. In this way we approximate a real wind profile and vertically varying settling velocity as a layered wind and settling velocity profile. A similar approach for the volcanic ash transport description was used in the past. It was firstly adopted by Suzuki (1983) then developed e.g. by Glaze and Self (1991).

In order to do this we divide the vertical domain into N_{layers} layers among which $N_{sources}$ point sources are distributed. Moreover, under the effects of wind, atmospheric turbulence and gravity it is assumed that the Gaussian distribution of particles spreads and settles into the underlying layer, while its centre horizontally translates.

The final position of the mass distribution centre at the ground $\vec{x}_{Gi} = (x_{Gi}, y_{Gi})$, is:

$$\vec{x}_{Gi} = \vec{x}_{0i} + \sum_k \vec{w}_k \Delta t_k, \quad (6)$$

where i identifies the point source layer, \sum_k indicates the sum on the generic layer between the point source and the ground, \vec{w}_k the horizontal wind velocity in the layer k , \vec{x}_{0i} the horizontal coordinates of the point source i and finally Δt_k is the residence time of particles in the layer k : $\Delta t_k = (z_k - z_{k-1})/v_{s,k}$. The code is able to handle point sources at arbitrary altitudes (not necessarily coinciding with the boundaries of the layers).

In the same way the mass of the point source spreads horizontally until it reaches the ground. The final variance of the mass distribution at the ground σ_{Gi}^2 , is

$$\sigma_{Gi}^2 = 2K \sum_k \Delta t_k. \quad (7)$$

Since wind profiles and settling velocities typically change significantly on a scale of a few kilometres, the

vertical domain should be divided into layers of few hundred meters in height.

Because of the linearity of Eq. (1), the total mass on the ground is computed as the sum of the contributions from each point source and each settling velocity class:

$$M_G(x, y) = \sum_{j=1}^{N_{vs}} \sum_{i=1}^{N_{sources}} \frac{M_i f_j}{2\pi\sigma_{Gi}^2} \times \exp\left[-\frac{(x-x_{Gi})^2 + (y-y_{Gi})^2}{2\sigma_{Gi}^2}\right], \quad (8)$$

where N_{vs} indicates the total number of settling velocity classes, M_i is the total mass emitted from the point source in the layer i ($\sum_i M_i = M_{tot}$, 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 ($\sum_j f_j = 1$).

When the settling velocity distribution is unknown but the particle size spectrum is known, the utility `VSET` permits granulometric data to be converted into velocity classes (see Section 3.2).

2.1. Initial and boundary conditions

The mass distribution in real eruption columns is governed by complex physical processes that the present model cannot account for (Sparks, 1986). In order to consider a mushroom-like shape for the column, typical of many explosive eruptions, we use an empirical formula modified from the original Suzuki formula (Suzuki, 1983):

$$S(x, y, z, t) = S_0 \left\{ \left(1 - \frac{z}{H}\right) \exp\left[A\left(\frac{z}{H} - 1\right)\right] \right\}^\lambda \times \delta(t - t_0) \delta(x - x_v) \delta(y - y_v) \quad (9)$$

where S_0 is the normalisation constant, x_v , y_v are the coordinates of the vent, H is the column height and A and λ (Suzuki coefficients) are two empirical parameters introduced in Pfeiffer et al. (2005). Theoretical and empirical observations on buoyant plumes (Morton et al., 1956; Sparks, 1986) show that the ratio H_B/H_T

between the height of buoyancy of the plume H_B and the maximum height H_T is usually around 3/4. We try to account for this considering A around 4, and λ is varied in the range $1 \leq \lambda \leq 5$ (see Fig. 1). The program `GENINP` (see Section 3.3) provides the values of S in a discrete number of points along z (point sources).

The output file of `HAZMAP` (when the code is used in “deposit mode”) contains the total mass accumulation (kg/m^2) for each grid point; however, with minor changes in the code, the particle velocity spectrum in each grid point can be generated.

3. Description of the program HAZMAP

On UNIX/Linux machines, `HAZMAP` is executed, by invoking the command `hazmap` directly from the shell prompt. This command runs the executable file of the program “`hazmap.f`”. At run-time, `HAZMAP` reads the input parameters from the file `hazmap.inp` that can be generated by `geninp`, and the information about the winds from the file `winds.dat`. `HAZMAP` reads its mode of operation in `hazmap.inp`. When `HAZMAP` runs in “deposit mode”, it generates the file `deposit.out`, otherwise, when it runs in “probability mode”, it generates the file `hazmap.out`. Both `deposit.out` and `hazmap.out` are ASCII files and can be further processed by other utilities such as the FORTRAN 77 computer program `HAZVIEW` freely available from the authors.

3.1. The input file hazmap.inp

The input parameters needed by `HAZMAP` are defined in the file `hazmap.inp` that can be created by hand or by an auxiliary utility (for example `GENINP`). These parameters are specified in the following order:

- The mode of operation. This is a numeric flag that can be specified as 0 (zero) or 1 (one). If the flag is zero, `HAZMAP` runs in “deposit mode”, and produces the file `deposit.out`. In this case `HAZMAP` reads the file `winds.dat`, BUT *only* the first wind profile is used for

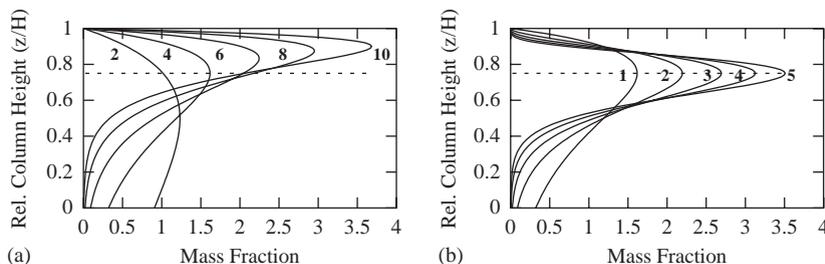


Fig. 1. Column shape: mass distribution inside the eruption column from Eq. (9). Relative column height is reported on the y-axis and mass fraction on the x-axis. On the left figure (a) $\lambda = 1$ and the indicated values of A were used. On the right figure (b) $A = 4$ and the indicated values of λ were used. The dashed line indicates the 3/4 of the column height.

the computation. The output files contains the ground accumulation expressed in kg/m^2 for each grid point. If, otherwise, the flag is set to 1 (one), HAZMAP reads all the file *winds.dat* and for each wind profile simulates the ground deposit. HAZMAP selects the area with a ground accumulation greater than a certain threshold (specified below), and marks the corresponding grid points contained inside this area. At the end of the computation, some grid points are rarely marked, whereas other points are marked more frequently. Using many wind profiles, this frequency approximates the probability that the ground accumulation overcomes the given threshold in each grid point. In this case the output file *hazmap.out* containing the frequency (normalised to 100) for each grid point is generated.

- A numeric flag specifying if a binary image is generated at the end of the computation. In this version of the code the image is generated only in PGM format. This file can be visualised in grey-tones or pseudocolors using a standard image browser that supports the PGM format. Among others, the public domain program *xv* can be used on UNIX platforms. If the flag is 1 (one) the image is generated, whereas if the flag is 0 (zero) no binary image file is created.
- The threshold (expressed in kg/m^2) considered for the hazard analysis. This parameter is always read, but is used only if the mode flag is 1 (one), that is in “probability mode”.
- The number of pixels in the horizontal directions of the computational grid.
- The dimensions (in meters) of the grid pixels in the horizontal directions.
- The coordinates of the left-bottom corner of the output matrix. These are used to geo-reference the output matrix.
- The atmospheric diffusion coefficient. Only one value is specified since isotropic horizontal diffusion is assumed. It is expressed in m^2/s .
- The number of settling velocity classes.
- The settling velocity classes (m/s).
- From here to the end of the file the point sources are specified. Each point source is specified by a group of three records:
 - The first record of this group contains three floating point numbers defining the source coordinates (x_p, y_p, z_p) . The origin of the coordinates is located at the centre of the computational domain. If the number of pixels of the grid is odd (*NX* and/or *NY*), the origin coincides with the central node, otherwise with the centre of the pixel.
 - The second record of the group specifies the total mass emitted by the corresponding point source.
 - The third record specifies the settling velocity spectrum of the particles emitted from the point source. Each floating point number defines the

mass fraction of the particles belonging to the corresponding settling velocity class defined above. The sum of these numbers should be close to unity to guarantee mass conservation. This is not strictly necessary if the user is not interested in simulating the whole settling velocity spectrum.

An example of file *hazmap.inp* with two point sources is reported in Table 1. Only numbers on the left side are read; comments are introduced here for clarity and are optional in the file.

3.2. The utility *vSET*

Generally the particle settling velocity is unknown, and only the particle size and density distribution are known.

vSET transforms particle size d and density ρ_p distributions into the particle settling velocity spectrum, assuming different particle shapes. The settling velocity v_s is computed as

$$v_s = \sqrt{\frac{4g\rho_p d}{3C_D\rho_a}} \quad (10)$$

Table 1
Sample of file *hazmap.inp*

0	Flag = 0 (Deposit mode)
0	Flag = 0 Do not generate binary file
400.	Hazard threshold (Not used in 'deposit-mode')
200 200	<i>NX NY</i> Number of grid pixels
350. 350.	<i>DX DY</i> Grid spacing (meters)
-35000.0	<i>Xoff, Yoff</i> Coordinates of the
35000.0	left-bottom corner
3000.0	Diffusion coefficient (m^2/s)
9	Number of settling velocity classes
1. 2. 3. 4. 5.	Settling velocity classes (m/s)
6. 7. 8. 9.	
0. 0. 500.	<i>X(1), Y(1), Z(1)</i> Coordinates of point source <i>N.1</i>
1.116E8	Mass emitted from point source <i>N.1</i> (kg)
.3 .17 .16 .13	Settling velocity distribution
.09 .07 .04 .02	<i>N.1</i>
.02	
0. 0. 1000.	<i>X(2), Y(2), Z(2)</i> Coordinates of point source <i>N.2</i>
1.6E8	Mass emitted from point source <i>N.2</i> (kg)
.3 .17 .16 .13	Settling velocity distribution
.09 .07 .04 .02	<i>N.2</i>
.02	
...	

where g is gravity, ρ_a is the density of air and the drag coefficient C_D is a specified function of the Reynolds number $R_e = \rho_a v d / \mu_a$ in the atmosphere ($\mu_a =$ air viscosity). Depending on a specified flag (see below), the present version of `vset` can use the Arastoopour et al. (1982)'s model (assuming spherical particles):

$$C_D = \frac{24}{R_e} (1 + 0.15 R_e^{0.687}) \quad R_e < 1000,$$

$$C_D = 0.44 \quad R_e \geq 1000 \quad (11)$$

or, other more accurate models that account for more general particle shapes such as Ganser (1993) and Pfeiffer et al. (2005).

Settling velocity changes with height, and a reliable altitude settling velocity dependence should be specified. If, a constant settling velocity is considered, it might be not realistic especially for very high eruption columns where such an effect can be important. For this purpose, in this version of the code, at the end of the program `hazmap.f`, a function called “fvcorr”, which accounts for altitude settling velocity dependence, was added. Since this model is intrinsically a first order approach and that for a given ground settling velocity class, the altitude settling velocity dependence of pumices or of lithics, does not change dramatically (see Pfeiffer et al., 2005), in order to reduce the computational time, we used a parameterisation for each settling velocity class at the ground irrespective of the kind of particle. In summary, for each settling velocity class at the ground $V_{s0} = V_s(0)$, a different parameterisation function $f = f(V_{s0}, z)$ can be introduced in order to reproduce, for example, the behaviour obtained in Pfeiffer et al. (2005):

$$V_s(z) = V_{s0} f(V_{s0}, z). \quad (12)$$

Although the use of the function “fvcorr” improves the estimates of the particle settling velocity in the higher region, the model still assumes that particle settle through the atmosphere at their terminal velocity that is not completely correct especially high in the atmosphere.

The input data needed by `vset` are read from the file `vset.inp`, with the following format:

- The first record specifies the model used to calculate the settling velocity: if it is equal to 1 Arastoopour et al. (1982)'s model is used; if it is equal to 2 Pfeiffer et al. (2005)'s model (using a shape factor $F = 0,43$) is used; if it is equal to 3 Ganser (1993)'s model (using a shape factor $F = 0,43$) is used.
- The second record specifies the number of the particle size classes n .
- The n following pairs of fields define the particle size class (first field), in Φ unit ($d = 2^{-\Phi}$ mm), and the weight percentage of the class (second field).
- Number of particle types.

- Number of the particle size classes and label for the first type of particle.
- The n following couples of fields define the density (first field) and the weight percentage (second field) of the particle types above specified.
- As above for the other kind of particles.
- ...

An example of file `vset.inp` is reported in Table 2. Only numbers on the left side are read; comments are introduced here for clarity and are optional in the file.

After executing `vset`, the output files `vset.prt` and `vset.vel` are generated. The files `vset.prt` and `vset.vel` are similar, in that both contain the same information on the particle settling velocity spectrum, but `vset.prt` is easier to be read. The records to be written in `hazmap.inp` can be read directly in the first block of records of `vset.prt`. This block is made of two columns, the first specifies the velocity and the second the weight percentage. The total mass percentage of the particles whose settling velocities are taken into account in the spectrum is specified in the next line. An example is reported in Table 3.

Table 2
Sample of file `vset.inp`

1	S.V. Model: 1 = Arastoopour et al. (1982), 2 = Pfeiffer et al. (2005), 3 = Ganser (1993)
6	Number of granulometric classes (Φ)
-1 10	Φ , Weight percentage of the granulometric class
0 20	
1 30	
2 20	
3 10	
4 10	
2	Number of particle types
6 'Type 1'	Number of granulometric classes, 'label for particle type'
2500 0	Density, Weight percentage of this kind of particles for $\Phi = -4$
2500 30	As above for $\Phi = -3$
2500 30	As above for $\Phi = -2$
2500 40	As above for $\Phi = -1$
2500 0	As above for $\Phi = 0$
2500 0	As above for $\Phi = 1$
6 'Type 2'	Number of granulometric classes, 'label for particle type'
2500 0	As above for other particle types
2600 30	
2500 30	
2700 20	
2800 20	
2500 0	

Table 3
Sample of partial file *vset.prt*

VSET. = 1.0	WT = 0.57
VSET. = 2.0	WT = 2.60
VSET. = 3.0	WT = 6.00
VSET. = 4.0	WT = 5.83
VSET. = 5.0	WT = 5.12
VSET. = 6.0	WT = 5.12
VSET. = 7.0	WT = 5.12
VSET. = 8.0	WT = 4.18
VSET. = 9.0	WT = 3.76
VSET. = 10.0	WT = 3.76
:	
TOTAL = 44.00	
:	

File *vset.prt* contains more detailed information about the settling velocity and density of the different kinds of particles for any granulometric class.

3.3. The utility GENINP

The input parameters needed by HAZMAP are read in the file *hazmap.inp*. This file can be created directly by hand or by invoking the command **geninp** that runs the executable file of the program “geninp.f”. GENINP computes the mass along the vertical column in a discrete number of points along z using Eq. (9). The input parameters needed by GENINP to create the file *hazmap.inp* are defined in the file *geninp.inp* and are specified in the following order:

- The first record defines the operation mode (0 deposit mode, 1 probability mode).
- The second record specifies if a binary image (PGM format) is generated (see Section 3.1).
- The third record specifies the total mass emitted by the corresponding point sources.
- The fourth record defines the number n of the settling velocity classes of the particles emitted from the point sources.
- The next n rows define the settling velocity spectrum of the particles emitted from the point sources. The first field defines the settling velocity class and the second field specifies the mass fraction of the particles belonging to the corresponding settling velocity class.
- Then, the threshold (expressed in kg/m^2) considered for the hazard analysis. This parameter is always read, but is only used in “probability mode”.
- The number of the pixels in the x - and y -directions of the computational grid.
- The dimensions (in meters) of the grid pixels in the x - and y -directions.
- The number of vertical steps.

Table 4
Sample of file *geninp.inp*

0	Operation mode
0	Flag = 0 do not generate binary image
5.0E11	Total Mass (kg)
9	Number of settling velocity classes
1.0 0.3021	Settling velocity(m/s) , Mass fraction
2.0 0.1663	
3.0 0.1612	
4.0 0.1316	
5.0 0.0923	
6.0 0.0672	
7.0 0.0355	
8.0 0.0225	
9.0 0.0213	
300.	Hazard threshold (Not used in 'deposit-mode')
200 200	NX NY Number of grid pixels
350. 350.	DX DY Grid spacing (meters)
32	Number of vertical steps
3000.	Diffusion coefficient (m^2/s)
16000.	Height of the column (m)
4. 1.	Suzuki coefficients (A and λ)

- The atmospheric diffusion coefficient. Only one value is specified since isotropic horizontal diffusion is assumed. It is expressed in m^2/s .
- The height of the column (expressed in meters).
- Two parameter defining the column shape, A and λ (Suzuki coefficients, see Eq. (9)).

An example of file *geninp.inp* is reported in Table 4. Only numbers on the left side are read; comments are introduced here for clarity and are optional in the file.

3.4. The input file winds.dat

The wind profiles used by HAZMAP are defined in the file *winds.dat*. In this file an arbitrary number of input profiles can be specified. If HAZMAP is used in “deposit mode”, then only the first wind profile is read and used. In “probability mode” all the wind profiles are used for producing the probability map. The file *winds.dat* has the following format:

- The first record defines the number of z -levels where the wind velocities are measured (NLEV).
- The following NLEV records specify the height of z -levels (in meters).
- One or more groups of NLEV records six fields (Year, Month, Day, Level, VX , VY). Only the velocity components VX and VY are used by

HAZMAP. The level number is also read by HAZMAP for an internal consistency check.

An example of file *winds.dat* with two wind profiles is reported in Table 5. Comments are included here for simplicity.

3.5. The output file

The output data are written in the ASCII files *hazmap.out* file (in probability mode) and in *deposit.out* file (in deposit mode). The format of this file is:

- The first record is the flag (copied from *hazmap.inp*) defining the mode of operation. If its value is 0 (zero), then the following values refer to the ground accumulation (kg/m²) at the grid nodes; if the flag is 1 (one), the following numbers refer to hazard probabilities (normalised to 100).
- In the second record the number of pixels in the *X* and *Y* directions are specified. These numbers are copied from the record N.4 of the file *hazmap.inp* (*NX*, *NY*).

- In the third record the *X* coordinates of the grid cells are reported (this record may be long).
- In the fourth record the *Y* coordinates of the grid cells are reported (this record also may be long).
- From the fifth record to the end-of-file (*NY* records), the ground accumulation values (or the probabilities) at the grid nodes are reported. In each record, *NX* values are reported from left to right. The records represent the output values from the top to the bottom of the interested region.

3.6. Compiling HAZMAP

HAZMAP is written in standard FORTRAN -77. Array and matrices dimensions are defined in the file *hazmap.inc*. Typically the lines corresponding to the command “parameter” need to be changed.

4. Applications

Previous versions of the HAZMAP model have been used in a variety of studies, such as the reconstruction of past

Table 5
Sample of file *winds.dat*

10						Number of Z-levels
1000.						Elevation of level N.1
2000.						Elevation of level N.2
2000.						Elevation of level N.3
4000.						Elevation of level N.4
5000.						Elevation of level N.5
6000.						Elevation of level N.6
7000.						Elevation of level N.7
8000.						Elevation of level N.8
9000.						Elevation of level N.9
10000.						Elevation of level N.10
1992	1	1	1	-7.822	.480	Wind velocity profile at level N.1
1992	1	1	2	-4.028	-1.040	Wind velocity profile at level N.2
1992	1	1	3	-.097	-2.852	Wind velocity profile at level N.3
1992	1	1	4	1.057	-2.233	Wind velocity profile at level N.4
1992	1	1	5	1.425	-1.672	Wind velocity profile at level N.5
1992	1	1	6	1.877	-1.728	Wind velocity profile at level N.6
1992	1	1	7	3.928	-3.358	Wind velocity profile at level N.7
1992	1	1	8	7.306	-4.089	Wind velocity profile at level N.8
1992	1	1	9	12.295	-3.731	Wind velocity profile at level N.9
1992	1	1	10	17.608	-2.951	Wind velocity profile at level N.10
1992	1	2	1	-7.342	.547	Wind velocity profile at level N.1
1992	1	2	2	-5.232	-1.341	Wind velocity profile at level N.2
1992	1	2	3	-.567	-2.143	Wind velocity profile at level N.3
1992	1	2	4	1.324	-3.108	Wind velocity profile at level N.4
1992	1	2	5	1.223	-1.443	Wind velocity profile at level N.5
1992	1	2	6	1.767	-2.027	Wind velocity profile at level N.6
1992	1	2	7	2.976	-3.041	Wind velocity profile at level N.7
1992	1	2	8	6.334	-4.165	Wind velocity profile at level N.8
1992	1	2	9	11.987	-3.429	Wind velocity profile at level N.9
...	Other wind profiles may follow

Plinian eruptions by best fitting of field data (Costa et al., 2001; Pfeiffer et al., 2005), tephra fallout risk mapping (Barberi et al., 1990), the evaluation of volcanic hazard for a certain exposed area (Barberi et al., 1992; Cioni et al., 2003) or for air traffic safety (Macedonio et al., 1994). All the above quoted papers can be considered examples of HAZMAP program applications. In this paper we briefly report just two simple examples. The first shows how the program operates when the mode flag in *hazmap.inp* is set 0 (deposit mode) and the second when it is set 1 (probability mode).

For the first example (deposit mode), in the *geninp.inp* file we use the same values reported in the sample shown in Table 4. Moreover we consider a simple wind blowing only in the *x*-direction with a linear vertical profile up to 12 km (where the maximum velocity is 24 m/s) and a constant profile above 12 km (12 m/s). The obtained isopachs of 10, 100 and 500 kg/m² are shown in Fig. 2. When the deposit mode is set and the input parameters are unknown, except for a certain number of deposit and granulometric observed values, HAZMAP can be used to estimate the other related quantities (e.g. erupted mass, column height) by best fitting the observed values.

For the second example (probability mode), we use the same *geninp.inp* file as the previous example but we employ a statistical set of recorded wind profiles (3125 wind profiles) is used. In Fig. 3, the probability map for ash loading greater than the threshold of 400 kg/m² is shown.

For example the contour line labelled “10” encloses the area where the probability of a mass load greater than 400 kg/m² is greater than 10%.

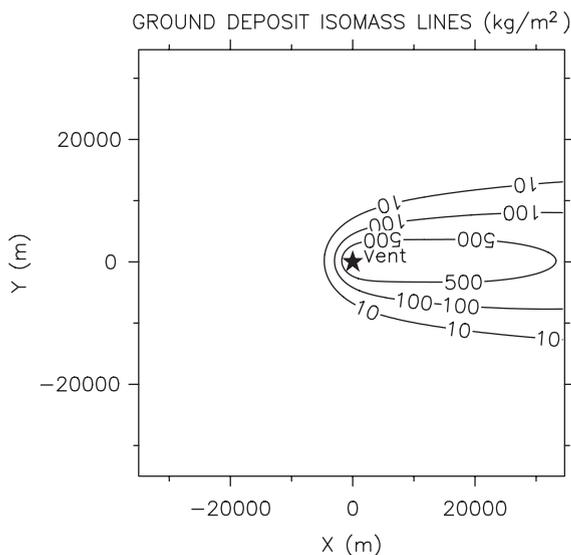


Fig. 2. Isopachs obtained with HAZMAP (deposit mode) with same input parameter values reported in Table 4 and a simple linear *x*-direction wind profile.

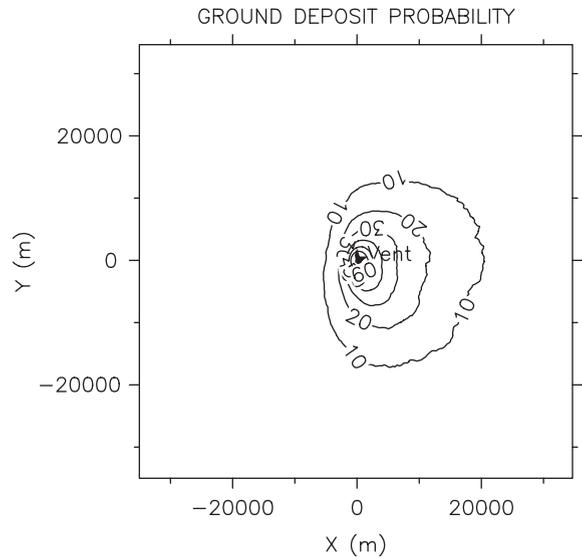


Fig. 3. Probability of a ground deposit greater than 400 kg/m² obtained with HAZMAP (probability mode) with same input parameter values reported in Table 4 and a statistical set of real wind profiles.

This probability mode run takes around ten minutes on a PC.

5. Limitations

Because of the many simplifying assumptions, the present model must be considered a zero-order model. For its application, the user needs to pay attention to the main limitations of applicability of HAZMAP that are basically summarised in the following:

- Validity of the use of the model is limited to areas far from the vent where the dynamics of the eruption column play a minor role. The results from Macedonio et al. (1988) and Armienti et al. (1988) suggest that the critical distance is approximately given by the height of the eruption column itself.
- Since it is assumed that the vertical diffusion and vertical wind components are negligible with respect to the horizontal ones, the model is intrinsically a 2D model and its results must to be considered inaccurate at lower atmospheric levels and in areas of considerable relief where terrain effects cannot be neglected (the maximum topographic height in the computational domain must be much smaller than the column height). For this reason the model cannot be applied in the reconstruction of tephra fallout from low eruption column.

- The horizontal wind components are considered constant in time and within the horizontal domain. This assumption holds for intermediate distances of the order of 100 km or more, but becomes less accurate over large distances.
- Finally, if the model is used without to take account for the variation of settling velocity with altitude, the results become inaccurate high in the atmosphere.

6. Conclusions

A simple zero-order model to reconstruct tephra fall deposit was presented. The model uses a semi-analytical approach that permits many simulations in a relatively short time on PCs. The model was previously applied with a satisfactory reproduction of various tephra deposits at a medium-ranges (10–200 km) from source.

HAZMAP has the potential to serve as a simple tool to predict ash fall for hypothetical or real eruptions of a given magnitude and a given wind profile. Using a statistical set of recorded wind profiles (and/or other input parameters) it also can be used to draw hazard maps from ash fall deposit.

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