HAZMAP-2.5.2

User Manual

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1   Introduction

HAZMAP-2.5.2 is a computer program for simulating sedimentation of volcanic particles from discrete point sources and to obtain the corresponding ground deposit (deposit mode). Moreover, HAZMAP-2.5.2 is able to evaluate the probability of overcoming a given loading threshold in the ground deposit by using a set of different wind profiles recorded in different days (probability mode). 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 Plinian column, subject to a given wind profile, 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 output file `hazmap-dep.out` file (deposit mode) or in a set of output files `hazmap-*.out` each corresponding to a given loading threshold (probability mode). Up to the version 2.2, the program HAZMAP was written in standard FORTRAN 77. The current version HAZMAP-2.5.2 was rewritten in FORTRAN 90 and includes some corrections and changes aimed to improve the performance and to generalize its applicability. The main change is related to way in which settling velocities are calculated. In the previous versions of HAZMAP, particle classes were discerned on the basis of their settling velocity class, irrespective of their diameter, density and shape. Moreover the variation of their settling velocity with height was accounted for using an approximate parameterization, based on the results of Pfeiffer et al. (2005), incorporated in the FORTRAN function FVCORR. Hence it was consistent with the settling velocity model proposed in Pfeiffer et al. (2005) only. In HAZMAP-2.5.2 settling velocities can be calculated using several models directly as function of particle diameters, densities, and shapes (calculated in module **settling.f90**). The variability of atmospheric properties with altitude is accounted for using a model of the U.S. Standard Atmosphere (1977), which furnishes the air density and viscosity at each elevation (subroutines **atmosphere.f90** (Carmichael, 2009) and **sutherland.f90**).
Finally all the files are now geo-referenced using a UTM coordinate system.
A backward compatibility is guaranteed, and HAZMAP-2.5.2 allows to use a particle spectrum specified in terms of settling velocities, with an optional settling velocity variation with the altitude through the function **fvcorr.f90**, as in Macedonio et al. (2005).

2   Ash transport model

HAZMAP-2.5.2 is based on a simple physical model which describes transport and sedimentation of volcanic particles (lapilli and ash) 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 first-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:

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

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), (Armienti 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:

$$
S(x, y, z, t) = \delta(t - t_0) \sum_{k}^{N_k} M_k \delta(x - x_v) \delta(y - y_v) \delta(z - z_k)
\tag{2}
$$

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:

$$\frac{\partial C_j}{\partial t} + w_x \frac{\partial C_j}{\partial x} + w_y \frac{\partial C_j}{\partial y} - v_{s,j} \frac{\partial C_j}{\partial z} = K_x \frac{\partial^2 C_j}{\partial x^2} + K_y \frac{\partial^2 C_j}{\partial y^2} + K_z \frac{\partial^2 C_j}{\partial z^2} \tag{3}$$

admits the exact analytical solution:

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

In the limit of $K_z \to 0$ the solution eq. (4) can be approximated by:

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

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:

$$\vec{x}_{Gi} = \vec{x}_{0i} + \sum_k \vec{w}_k \Delta t_k \tag{6}$$

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:

$$\sigma_{Gi}^2 = 2K \sum_k \Delta t_k \tag{7}$$

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:

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

where N_{v_s} 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 ($\sum_j f_j = 1$).
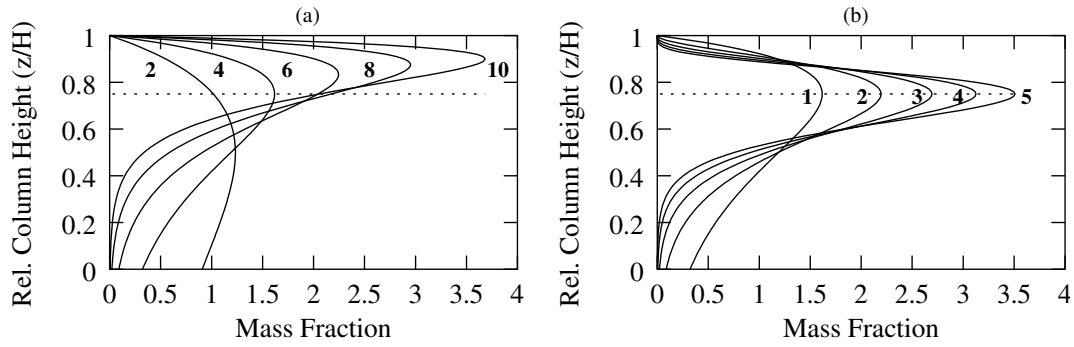
Figure 1: Column shape: mass distribution inside the eruption column from eq. (9). Relative column height is reported on the y-axis and a value proportional to the mass fraction on the x-axis. On the left figure (a) $\lambda = 1$ and the indicated values of A were used. On the right figure (b) $A = 4$ and the indicated values of λ were used. The dashed line indicates the 3/4 of the column height. Mass fractions generated by GENINP are normalized to 1.

The mass distribution in real eruption columns is governed by complex physical processes (Sparks, 1986), that the present model cannot account for. 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):

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

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 (here referred as "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).

However, the direct use of eq. (9) leads to a null mass at ($z = H$) and could lead to an incorrect mass distribution when the number of vertical layers is small and/or A is large. In HAZMAP-2.5.2 we use a better discretization of the vertical column to avoid these inconveniences. Here, in order to evaluate the vertical mass distribution, the column is subdivided into layers and the mass is assumed to be proportional to the integral of eq. (9) in that layer. For example, if the column is discretized in N_s sources located at different equispaced elevations $z_i = i * \Delta z$ (where $i = 1, ..., N_s$ and $\Delta z = H/N_s$), than the mass in each source point is:

$$S_i = \int_{z_i - \Delta z/2}^{z_i + \Delta z/2} S(x_v, y_v, z, t)\, dz \tag{10}$$

The integrals (10) are simply evaluated, after observing that:

$$\int S(x_v, y_v, z, t)\, dz = S_0 \frac{H}{(A\lambda)^{\lambda+1}} \Gamma_L\left(\lambda + 1, A\lambda(1 - \frac{z}{H})\right) \delta(t - t_0)\delta(x - x_v)\delta(y - y_v) \tag{11}$$

where Γ_L is the lower Incomplete Gamma function defined by:

$$\Gamma_L(a, x) = \int_0^x \xi^{a-1} e^{-\xi} d\xi \tag{12}$$

The values of the mass S_i distributed along the z_i point sources, based on the integrals eq. (10), (11) and (12), are evaluated by the program GENINP (see Sec. 3.1.2) in subroutine `isuzuki.f90`. Moreover, instead of using the default mass distribution based on the Suzuki formula, GENINP also allows the user to provide a list of source points arbitrarily distributed and with given total mass fraction (see flag SMODEL in the input file `geninp.inp` described in Sec. 3.1.2).

3   Description of the program hazmap

On UNIX/Linux machines, HAZMAP-2.5.2 is executed, by invoking the command **hazmap** directly from the shell prompt. This command runs the executable file of the program `hazmap.f90`. At run-time, HAZMAP-2.5.2 reads the input parameters from file `hazmap.inp` and the information about the winds from file `winds.dat`. For simplicity, the utility GENINP may be used to generate file `hazmap.inp` starting from a simpler input file (file `geninp.inp`). HAZMAP-2.5.2 is able to operate in three different modes selected by a proper flag (flag MODE) defined in the input file `hazmap.inp`. Possible choices are *i*) "deposit mode" (set flag MODE=0 for generating a single deposit), "probability mode" (set flag MODE=1 for generating probabilities based from many wind profiles), or "barycenters mode" (set flag MODE=2 for generating the list of the center of mass of the deposits due to different wind profiles and particle classes). Concerning the output format, there are four choices, as described in Sec. 3.2.

3.1   The input files

3.1.1   The input file `hazmap.inp`

The input parameters needed by HAZMAP-2.5.2 are defined in the file `hazmap.inp` that can be created by hand or by the auxiliary utility GENINP (recommended). GENINP generates HAZMAP-2.5.2 input file including some comments that facilitate the reading (see Sec. 3.1.2). These parameters are specified in the following order:

- The mode of operation (flag MODE). This is a numeric flag that can be specified as 0 (zero), 1 (one) or 2 (two). If the flag is zero, HAZMAP-2.5.2 runs in "deposit mode", and produces the output file in the format defined by the user. In this case HAZMAP-2.5.2 reads the file `winds.dat`, BUT *only* the first wind profile is used for 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-2.5.2 reads all the file `winds.dat` and for each wind profile simulates the ground deposit. HAZMAP-2.5.2 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 containing the frequency (normalised to 100) for each grid point is generated. HAZMAP-2.5.2 is able to operate with one or more loading thresholds simultaneously. In this last case, HAZMAP-2.5.2 produces different output files, numbered consecutively and each corresponding to the specified threshold, in the same order as specified in the input file. Starting from HAZMAP-2.5.2, MODE=2 is allowed. In this case, `hazmap` produces a list of the coordinates of the center of mass of the deposit related to each particle class and wind profile (an example is reported in `Examples/example5`).

- A numeric flag (flag GRIDTYPE) specifying if the computational grid is regular, *i.e.* flag 0 (zero), or irregular, *i.e.* flag 1. In the case of flag 1 the irregular grid is furnished through `grid.inp`. The file `grid.inp` is an ASCII file formed of a record indicating the number of points N_{pts} followed by N_{pts} lines containing three records that denote a point label and a couple representing the UTM coordinate of the point (see Table 5 and Sec. 3.1.4).

- A numeric flag (flag VMODEL) specifying the settling velocity model. If this flag is 0 (zero) the settling velocity classes and distribution are specified by the user. If the flag is different from 0 particle classes are defined in accord to the user-defined particle diameter, density, and shape. If VMODEL=1 Arastoopour et al. (1982)'s model is used; if VMODEL=2 Ganser (1993)'s model is used; if VMODEL=3 Wilson and Huang (1979) and Walker et al. (1971)'s model is used (as described in Pfeiffer et al. (2005) using a user-defined shape factor F); and if VMODEL=4 the model of Dellino et al. (2005) is used. Additional settling velocity models could be specified in module **settling.f90**.

- A numeric flag (flag IFVOFZ) specifying whether the settling velocity is a function of the height Z (considered starting from the sea level) or not. If this flag is 0 (zero) settling velocity is calculated at sea level and does not change with height; if the flag is 1 settling velocity changes with height

in accord to the user-defined model and assuming the U.S. Standard Atmosphere (1977) properties calculated as in Carmichael (2009). When the settling velocity spectrum is defined by the user (flag VMODEL=0), the variation of the settling velocity with altitude is approximated as in Pfeiffer et al. (2005), through the function **fvcorr.f90**.

- A numeric flag specifying whether the file `grid.out`, containing a list of cells coordinate, is printed (flag equal 1) or not (flag equal 0).

- A numeric flag (flag IFWSPE) specifying whether the file `hazmap-spe.out`, containing particle spectra at each ground point, is printed (IFVSPE=1) or not (IFWSPE=0). Please, consider that activating this flag with a grid with many points will produce a large file.

- A numeric flag (flag VSETOUT specifying whether the file `vset.out`, containing the settling velocity for each particle and at different quotes, is printed (flag equal 1) or not (flag equal 0).

- A numeric flag specifying the format of the output file (flag OUTFMT). This flag has to be set equal to 1 for creating the output in the case of an irregular grid (*i.e.* GRIDTYPE=1). In this case a file called `hazmap-dep.out` (if MODE=0) or `hazmap-`i_{thrs}`.out` (if MODE=1) is created (for the format of output files see Sec. 3.2). The following values of flag OUTFMT (2, 3 or 4) produce regulard grids and are associated with flag GRIDTYPE=0. If OUTFMT=2, a file `hazmap.out` containing values of deposits (MODE=0) or of probabilities (MODE=1) is created. This file can be visualized using the utility HAZVIEW distributed with this package. If this flag is equal to 3 a file `hazmap.grd` in GRD ASCII format containing values of deposits (MODE=0) or of probabilities (MODE=1) is created. In this last case (MODE=1) HAZMAP-2.5.2 generates a sequence of files named `hazmap-001.grd`, `hazmap-002.grd`, and so on, up to `hazmap-`NTHR`.grd`, where NTHR is the number of loading thresholds specified below. If OUTFMT=4 a file `hazmap.grd` in GRD BINARY format containing values of deposit loadings (MODE=0) or a sequence of numbered files (as above) containing the probabilities (MODE=1) is created. The files GRD produced with OUTFMT=3 and OUTFMT=4 can be visualized using the commercial software SURFER$^{\copyright}$.

- Two fields defining the number of pixels in the horizontal and vertical directions of the computational grid (used if GRIDTYPE=0).

- Two fields defining the number of pixels in the horizontal and vertical directions of the computational grid (used if GRIDTYPE=0).

- This integer (NTHR) denotes the number tephra load thresholds. This parameter is used only if the mode flag is 1 (one), that is in "probability mode".

- NTHR lines denoting the threshold (expressed in kg/m^2) considered for the hazard analysis. This parameter is used only if the mode flag is 1 (one), that is in "probability mode".

- 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 particle classes N_{pc}.

- N_{pc} lines defining the particle classes. If the flag for settling velocity model (VMODEL) was set to zero, then each record has one field containing the settling velocity (m/s) of the particles in that class. On the contrary, if flag VMODEL was set different different than zero, each record contains three fields: particle diameter, density and shape factor of the corresponding particle class.

- The number of source points N_{sp}.

- From here to the end of the file the point sources are specified. Each point source is specified by a group of $N_{pc} + 2$ records:

– The first record of this group contains three floating point numbers defining the source coordinates (x_p, y_p, z_p) in UTM.

– The second record of the group specifies the total mass emitted by the corresponding point source.

– The following N_{pc} records specify the particle spectrum emitted from the point source. Each record defines the mass fraction of the particles belonging to the corresponding class defined above. The sum of these numbers should be equal to one to guarantee that all the mass of the corresponding point source is considered in the computation. This is not strictly necessary if the user is not interested in simulating the whole particle spectrum.

An example of file `hazmap.inp` with 40 point sources is reported in Table 1 (the file is truncated). Only numbers on the left side are read; comments are introduced here for clarity and are optional in the file (comments are automatically generated if file `hazmap.inp` is generated by the utility GENINP).

3.1.2 The utility geninp

The input parameters needed by HAZMAP-2.5.2 are read in the file `hazmap.inp`. As specified above, this file can be created directly by hand or by invoking the command **geninp** that runs the executable file of the program `geninp.f90`. The use of GENINPis strongly recommended for creating the file `hazmap.inp`. Regarding the source distribution GENINP can either read it directly from the file `sources.inp`) or, more simply, computes the mass along the vertical column in a discrete number of points using eq. (9), (11) and (12). 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 (flag MODE). This flag is 0 for "deposit mode" or 1 for "probability mode".

- The second record specifies the grid type (flag GRIDTYPE): 0=uniform grid, 1=irregular grid read from file `grid.inp` (see also the description of flag GRIDTYPE is Sec. 3.1.1).

- A numeric flag specifying the settling velocity model (flag VMODEL). For the description refer to flag VMODEL in Sec. 3.1.1.

- A numeric flag specifying whether the settling velocity is a function of the height Z or not. See the description of flag IFVOFZ in Sec. 3.1.1.

- A numeric flag specifying whether the file `grid.out`, containing a list of cells coordinate, is printed by **hazmap** (flag equal 1) or not (flag equal 0).

- A numeric flag (IFWSPE) specifying whether the file `hazmap-spe.out`, containing particle spectra at each point, is printed by **hazmap** (flag equal 1) or not (flag equal 0).

- A numeric flag (flag VSETOUT) specifying whether the file `vset.out`, containing the settling velocity profiles for each particle, is printed by **hazmap** (flag equal 1) or not (flag equal 0).

- A numeric flag (OUTFMT) specifying the format of the output file generated by **hazmap**. For the descrition, refer to flag OUTFMT in Sec. 3.1.1.

- A record defining the number of pixels in the horizontal and vertical directions (`NX,NY`) of the computational grid (used if GRIDTYPE=0).

- The dimensions (in meters) of the grid pixels (`DX,DY`) of the computational grid (used if GRIDTYPE=0).

- The coordinates of the center of the computational grid (`xcenter,ycenter`). This is used if GRIDTYPE=0.

- The total erupted mass (kg).

- A flag (SMODEL) defining the vertical source distribution model. When this flag is 0 (zero) the list of source points with the corresponding mass fraction is read from file `sources.inp`. Otherwise, when this flag is 1, the vertical mass distribution is generated by using the Suzuki distribution (see Sec. 2).

- Three records defining the UTM coordinate of the eruptive vent (X_v, Y_v, Z_v). These parameters are used if SMODEL=1.

- The height of the top of the column (HMAX), expressed in meters a.s.l. Please, note that the actual column length is HMAX-Z_v. This parameter is used if SMODEL=1.

- The number of steps for vertical discretization. This parameter is used if SMODEL=1.

- Two parameter defining the column shape, A and λ (the Suzuki coefficients described in Sec. 2). These parameters are used if SMODEL=1.

- The atmospheric turbulence diffusion coefficient. Only one value is specified since vertical diffusion is assumed to be negligible. It is expressed in m^2/s.

- This record (NTHR) denotes the number tephra load thresholds. This parameter is used only if the mode flag is 1 (MODE=1), that is in "probability mode".

- The NTHR thresholds (expressed in kg/m^2) considered for the hazard analysis. This parameter is used only if the mode flag is 1 (one), that is in "probability mode".

- This record defines the number (NPC) of particle classes emitted from the point sources. Each class is defined (see next records) by a settling velocity class and the percentage of the mass in that class (if flag VMODEL=0) or by a triplet denoting particle diameter, density and shape characterizing each class and the percentage of the mass in that class (flag VMODEL different from 0).

- The next NPC rows define the spectrum of the particles emitted from the point sources. If the flag for the settling velocity model is set equal to 0 (VMODEL=0), the first field defines the settling velocity class and the second field specifies the weight percent of the particles belonging to the corresponding settling velocity class. If flag VMODEL is not equal to 0, it is necessary to specify four fields, each corresponding to each particle type, specifying the particle diameter, density, shape, and relative percentage. Please note that GENINP needs the weight percent of the particles in each class, whereas in `hazmap.inp` the spectra in the source points are defined by the mass fractions. The utility GENINP performs this translation.

An example of file `geninp.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.

When the mass distribution is specified through an external list (parameter SMODEL=1), GENINP reads file `sources.inp`. The first record of this file indicates the number of source points, than for each source point, the coordinates X,Y,Z and the fraction of the total mass of the corresponding point are specified. The sum of all the mass fractions should be 1. An example of file `sources.inp` is reported in Table 3.

3.1.3 The input file `winds.dat`

The wind profiles used by HAZMAP-2.5.2 are defined in the file `winds.dat`. In this file an arbitrary number of input profiles can be specified. If HAZMAP-2.5.2 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 specified (parameter NLEV).

- The following NLEV records specify the height of the z-levels (in meters).

- One or more groups of NLEV records, each with six fields (Year, Month, Day, Level, VX, VY). Only the velocity components VX and VY are used by HAZMAP-2.5.2. The level number is also read by HAZMAP-2.5.2 for an internal consistency check.

An example of file `winds.dat` with two wind profiles is reported in Table 4. Comments are included here for simplicity and are optional in the file. Please note that the wind file reported in Table 4 contains z-levels from 1000 to 10000 m, spaced by 1000 m (for simplicity). However, wind files contained in the directory `Examples` contain winds between 500 and 25000 m with 500 m spacing and were used for producing the output of `hazmap` in this document.

3.1.4 The input file `grid.inp`

This version of HAZMAP-2.5.2 allows the user to specify a list of arbitrarily distributed points and to evaluate the deposit loading or hazard in the specified points. The list of ground points is specified in file `grid.inp`, which contains a first record containing the number of the grid points (parameter NPTS), and a sequence of records each composed by three fields: an alphanumeric label (max 6 characters without spaces) and the coordinates X and Y of the point. This file is read if flag GRIDTYPE is set to 1 in file `hazmap.inp` (or `geninp.inp`).

3.2 The output files

3.2.1 The output files `hazmap.out`, `hazmap-dep.out` and `hazmap-`i_{thr}`.out`

As we explained in Sec. 3.1.1 the user has four different options for the format of the output file. The name of the file depends on the selected option.

1. If the flag for the format of the output files (flag OUTFMT) is 1 then the output data are written in the file `hazmap-dep.out` (in deposit mode) or in the N_{thr} files `hazmap-`i_{thr}`.out` (in probability mode). The structure of the file is the following:

   - The first record contains flag MODE
   - The second record containts the number of grid points (parameter NPTS).
   - The following NPTS records are composed by 4 fields: point label, X, Y, VALUE

   where VALUE indicates the deposit loading (if flag MODE=0) or the probability to overcome a loading threshold (if flag MODE=1). A sample of this file is reported in Table 6 (comments on the right are not written by `hazmap`).

2. If the flag for the format of the output files (OUTFMT) is 2 then the output data are written in the ASCII file `hazmap.out`. The format of this file is different if `hazmap` was run in "deposit mode" (flag MODE=0) or in "probability mode" (flag MODE=1).

   - When flag MODE=1 ("deposit mode"), the format of the output file is:
     - The first record is the MODE flag defining the mode of operation. If its value is 0 (zero), then the following values refer to the ground accumulation (kg/m^2) 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 (NX and NY).
     - The third record contains the grid spacings DX and DY.
     - The fourth record contains the coordinates of the center of the left-bottom cell.
     - From the fifth record to the end-of-file (NY records), the ground accumulation values 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.
   - If flag MODE=1 ("probability mode"), the format of the output file is:

– The first record is the MODE flag defining the mode of operation. If its value is 0 (zero), then the following values refer to the ground accumulation (kg/m^2) at the grid nodes; if the flag is 1 (one), the following numbers refer to hazard probabilities (normalised to 100).

– The second records contains the value of NTHR, the number of loading thresholds.

– The third record contains the list of the loading thresholds.

– The fourth record contains the number of pixels in the X and Y directions (NX and NY).

– The fifth record contains the grid spacings DX and DY.

– The sixth record contains the coordinates of the center of the left-bottom cell.

– From the seventh record to the end-of-file, the probabilities at the grid nodes are reported, for each loading threshold. These are NTHR blocks (corresponding to a different loading threshold), each of NY records. 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. If the flag for the format of the output files (OUTFMT) is 3 then the output data are written in the file `hazmap.grd` in ASCII GRD format. The structure of a GRD format file is described in Table 7 and the meaning of the used symbols is the following:

- NX : Number of grid points along x-direction.

- NY : Number of grid points along y-direction.

- XO : x-coordinate (UTM in m) of the grid bottom left corner.

- XF : x-coordinate (UTM in m) of the grid top right corner point.

- YO : y-coordinate (UTM in m) of the grid bottom left corner point.

- YF : y-coordinate (UTM in m) of the grid top right corner point.

- VAL : Value at each grid point. It consists of an array of NX×NY values stored starting from the bottom-left corner and moving towards right then up towards the top of the domain.

4. If the flag for the format of the output files is 4 then the output data are written in the file `hazmap.grd` in ASCII BINARY format. The structure of the file is the same as for the previous case.

3.2.2   The output file `vset.out`

File `vset.out` is written by HAZMAP-2.5.2 when flag SETOUT is set to 1 (see Sec. 3.1.1 and 3.1.2). This file contains the settling velocities for each particle type defined in the input file `hazmap.inp` (or `geninp.inp`), evaluated at each quote of the different z-layer. The variation of the settling velocity with the quote is affected by flag IFVOFZ. When IFVOFZ=0 (specified in `hazmap.inp` or `geninp.inp` as described in Sec. 3.1.1 and 3.1.2), the settling velocity of each particle type is evaluated at sea level and is considered independent of the quote. On the contrary, when IFVOFZ=1, the settling velocity at differet quotes is evaluated by considering the air density and viscosity corresponding to the quote of the z-layer, assuming the US. Standard Atmosphere 1977 (Carmichael, 2009). The format of file `vset.out` is the following:

- The first record contains two integer fields: the number of particles types (N_{pc}) and the number of z-layers (N_{lev}).

- The second record contains the quotes of the z-layers where the settling velocities are avaluated (this record contains N_{lev} fields).

- The following N_{pc} records contain the settling velocity of the different particle classes. Each record contains N_{lev} fields, each corresponding to a different z-level.

An example of file `hazmap-spe.out` is reported in Table 8.

3.2.3 The output file `grid.out`

HAZMAP-2.5.2 is able to evaluate ash deposits (or hazard values) on uniform grids (internally generated) or on sparse points (supplied in file `grid.inp`). File `grid.out` represents the dump of the grid points used by HAZMAP-2.5.2 and has the same structure of file `grid.inp`. When the the grid is supplied externally, file `grid.out` contains the same grid points specified in file `grid.inp`, including the labels of the points. Instead, when the grid is generated internally (uniform grid), the grid points are listed starting from the bottom-left corner, left to right (inside each row),up to the upper-left corner. This order is used just for simplicity because the order of computation of grid points is irrelevant in `hazmap-2.5.2`. With the internally generated uniform grid, the label names are numbered starting from 0000001 up to 9999999. The label length in the output file `grid.out` depends on the number of grid points, and can contain up to a maximum of 7 figures (this limit is defined by the parameter LABLEN in file `hazmod.f90` and could be modified if necessary). Parameter MAXLAB also affects the maximum label length of the externally supplied grid points. An example of file `grid.out` is reported in Table 9.

3.2.4 The output file `hazmap-spe.out`

File `hazmap-spe.out` is written by HAZMAP-2.5.2 when flag IFWSPE is set to 1 (see Sec. 3.1.1 and 3.1.2). This file contains the mass fractions of each particle type, for each grid point where hazmap evaluates the deposit. The format of file `hazmap-spe.out` is the following:

- The first record contains two integer fields: the number of grid points (NPTS) and the number of particles types (N_{pc}).

- The following NPTS records contain ($N_{pc} + 1$) fields. The first field is the alphanumeric label of the grid point, whereas the following N_{pc} floating point fields are the mass fractions of the corresponding particle type in the given ground point.

An example of file `hazmap-spe.out` is reported in Table 10.

4 Installing HAZMAP-2.5.2

To install HAZMAP-2.5.2 on a Unix/Linux machine, uncompress and unpack the tar file, then go to the `hazmap-2.5.2` directory:

```
$ tar xzvf hazmap-<version>.tar.gz
$ cd hazmap-<version>
```

Inside directory `hazmap-2.5.2` issue the following commands:

```
$ ./configure
$ make
$ make install
```

These commands compile the `hazmap` and `geninp` programs and install them under the directory `$HOME/bin`, where `$HOME` is your home directory.

Once you have installed the binary codes, you can remove the program binaries and object files from the source code directory by typing `make clean`. To also remove the files that 'configure' created (so you can compile the package for a different kind of computer), type `make distclean`.

4.1 Compiler options

Some systems require unusual options for compilation or linking that the 'configure' script does not know about. Run `./configure --help` for details on some of the pertinent environment variables.

You can give 'configure' initial values for configuration parameters by setting variables in the command line or in the environment.

If your system does not set automatically the fortran compiler and/or the fortran compiler optimizzation flag (`FCFLAGS=-O` or `FCFLAGS=-O2`, etc.), we stongly suggest you to enable the optimizer. This will improve the speed of `hazmap`. Example:

```
$ ./configure FC=gfortran FCFLAGS=-O
```

4.2 Installation path

By default, 'make install' installs the package's commands under '$HOME/bin', where '$HOME' is your home directory. You can specify an installation prefix other than '$HOME' by giving 'configure' the option '–prefix=PREFIX', where PREFIX must be an absolute path name. The subdirectory name `bin` is automatically appended to the PREFIX directory, so that the execution path becomes `PREFIX/bin`.

To run `geninp` and `hazmap` it is very important that your shell path includes the directory where `geninp` and `hazmap` are installed (`$HOME/bin` by default). If your are not familiar with how to extend the execution PATH of your shell, ask your system manager.

4.3 GPU support

This version of `hazmap` supports NVIDIA GPUs based on CUDA language. The CUDA version is activated at configuration level with the command:

```
$ ./configure --with-cuda=<cuda_root_directory>
```

where `<cuda_root_directory>` is the path of the directory where CUDA is installed, i.e: the directory containing the subdirectories `include`, `lib` and/or `lib64`. For compilation of the CUDA driver (written in `C` language), the NVIDIA `C` compiler (`nvcc`) is required. HAZMAP needs CUDA architecture compatibility `sm_20`.

4.4 Uninstalling hazmap

Within the hazmap directory, you can type 'make uninstall' to remove the installed files. This command removes just the installed binary files but leaves all the source directory tree.

5 Applications

Previous versions of the HAZMAP model have been used in a variety of studies, such as the reconstruction of past Plinian eruptions by best fitting of field data (Pfeiffer et al., 2005; Costa et al., 2009; Bonasia et al., 2010), tephra fallout risk mapping (Barberi et al., 1990; Macedonio et al., 2008), 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 papers cited above contain few examples application 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 2. 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/m^2 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-2.5.2 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/m^2 is shown.

For example the contour line labelled "10" encloses the area where the probability of a mass load greater than 400 kg/m^2 is greater than 10%. This run, in probability mode, takes around ten minutes on a PC.

6 Limitations

Because of the many simplifying assumptions, the present model must be considered a first-order model. For its application, the user needs to pay attention to the main limitations of applicability of HAZMAP-2.5.2 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 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.

7 Conclusions

HAZMAP-2.5.2 is a computer code, written in FORTRAN-90, based on a first-order, semi-analytical model, for simulating volcanic ash dispersal. This allows to perform 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 a source.

HAZMAP-2.5.2 has the potential to serve as a simple tool to estimate 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.

Acknowledgments

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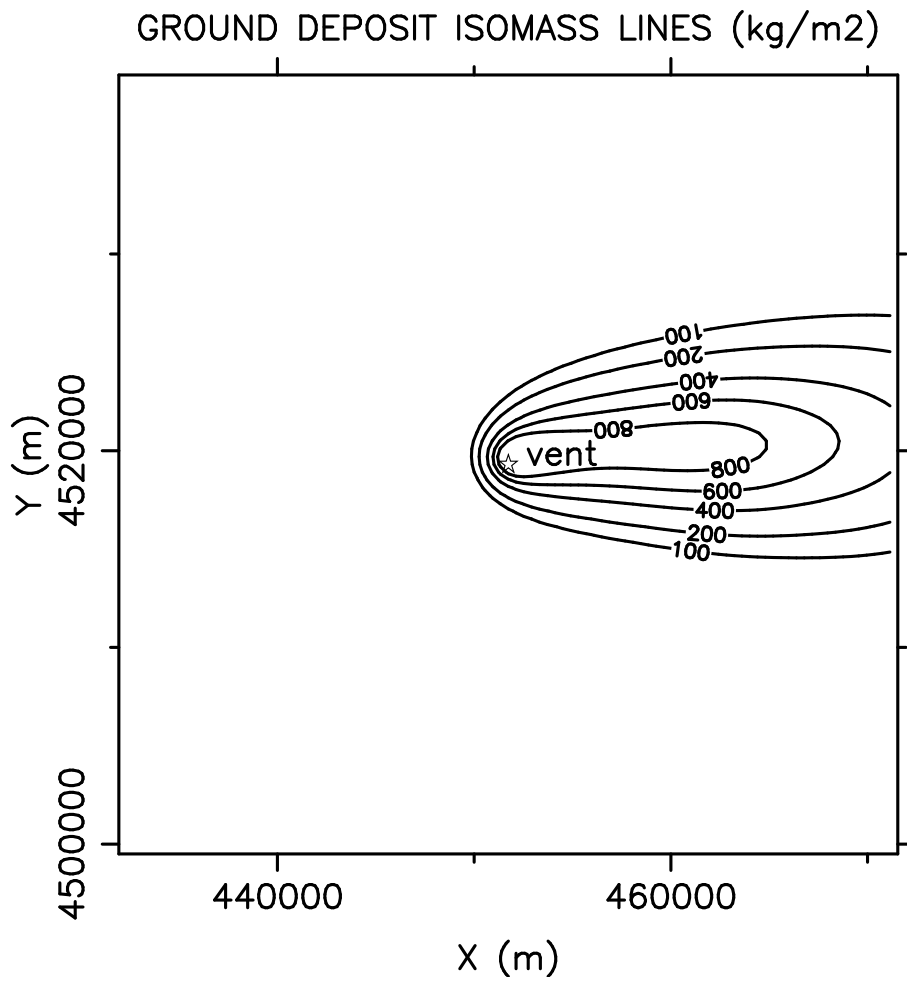
Figure 2: Isopachs obtained with HAZMAP-2.5.2 (deposit mode) with the same input parameter values reported in Table 2 and a simple linear x-direction wind profile.
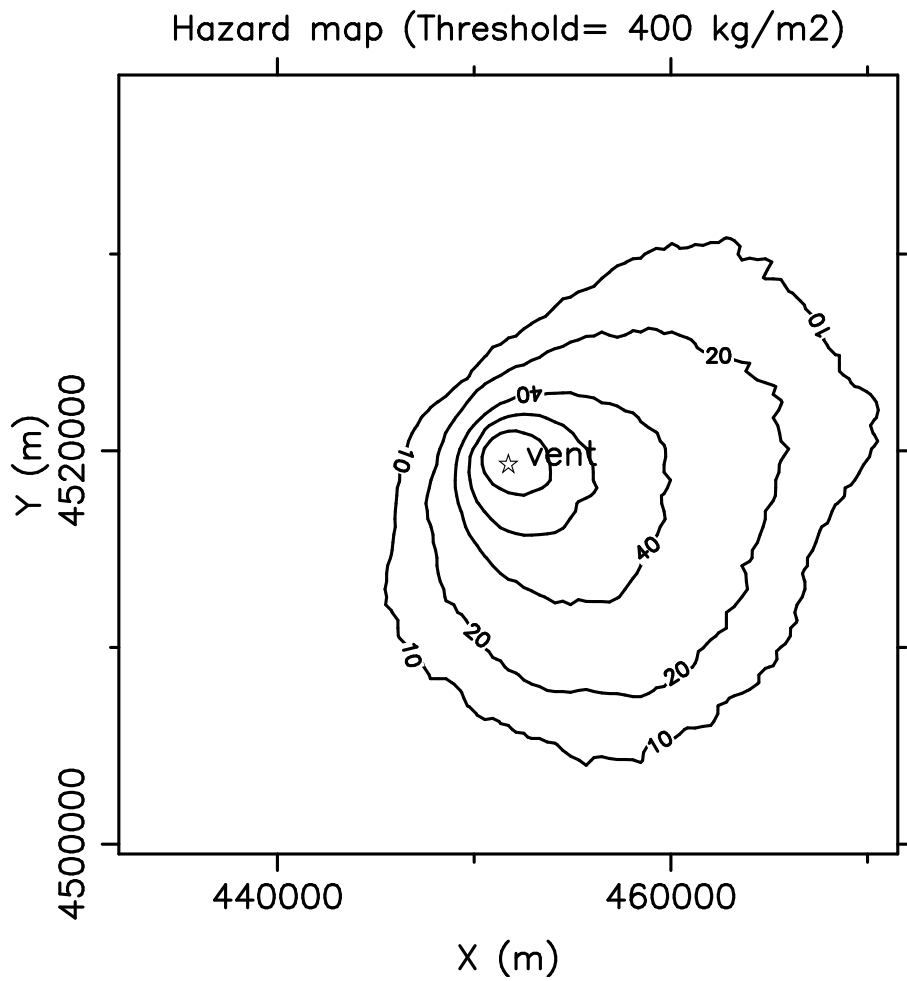
Figure 3: Probability map to overcome a ground deposit of 400 kg/m^2 obtained with HAZMAP-2.5.2 (in probability mode) with the same input parameter values reported in Table 2 and a statistical set of real wind profiles.

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Table 1: Sample of file `hazmap.inp`

```
0                 # Mode (0=deposit, 1=hazard map, 2=deposit barycenters)
0                 # Grid_type (0=uniform, 1=from file)
1                 # Settling velocity model
1                 # Settling velocity is constant in Z
0                 # Write list of cells coord. (file grid.out)
0                 # Flag: write particles spectra
0                 # Flag: write settling velocity profile
2                 # Format of the output file
100 100           # Number of grid cells (used if grid_type=0)
400.0   400.0     # Dimensions of the cells (used if grid_type=0)
  5               # Number of thresholds (used if mode=1)
 100.00           # Loading threshold (used if mode=1)    1
 200.00           # Loading threshold (used if mode=1)    2
 300.00           # Loading threshold (used if mode=1)    3
 400.00           # Loading threshold (used if mode=1)    4
 500.00           # Loading threshold (used if mode=1)    5
 5000.0           # Diffusion coefficient
    10            # Number of particles types
0.15620E-04 0.14000E+04 0.10000E+01 # Diam,dens,psi particle type    1
0.31250E-04 0.14000E+04 0.10000E+01 # Diam,dens,psi particle type    2
0.62500E-04 0.14000E+04 0.10000E+01 # Diam,dens,psi particle type    3
0.12500E-03 0.17000E+04 0.10000E+01 # Diam,dens,psi particle type    4
0.25000E-03 0.17000E+04 0.10000E+01 # Diam,dens,psi particle type    5
0.50000E-03 0.25000E+04 0.10000E+01 # Diam,dens,psi particle type    6
0.10000E-02 0.25000E+04 0.10000E+01 # Diam,dens,psi particle type    7
0.20000E-02 0.25000E+04 0.10000E+01 # Diam,dens,psi particle type    8
0.40000E-02 0.25000E+04 0.10000E+01 # Diam,dens,psi particle type    9
0.80000E-02 0.25000E+04 0.10000E+01 # Diam,dens,psi particle type   10
36                            # Number of vertical source points
451737.0 4519302.0   500.0   # Coordinates (x,y,z) of source      1
0.48915E+10                  # Total mass of source        1
0.70000E-01                  # Mass fraction particle type    1
0.10000E+00                  # Mass fraction particle type    2
0.12000E+00                  # Mass fraction particle type    3
0.21000E+00                  # Mass fraction particle type    4
0.17000E+00                  # Mass fraction particle type    5
0.10000E+00                  # Mass fraction particle type    6
0.90000E-01                  # Mass fraction particle type    7
0.80000E-01                  # Mass fraction particle type    8
0.50000E-01                  # Mass fraction particle type    9
0.10000E-01                  # Mass fraction particle type   10
451737.0 4519302.0  1000.0   # Coordinates (x,y,z) of source      2
...
```

Table 2: Sample of file `geninp.inp`

```
0                       # Mode (0=deposit; 1=hazmap)
0                       # Grid type (0=uniform, 1=from file)
1                       # Settling velocity model
1                       # Settling velocity is a function of Z
0                       # Write list of cell coordinates (file grid.out)
0                       # Write particles spectra
0                       # Write settling velocities (file vset.out)
2                       # Format of the output file
100 100                 # Number of grid cells (NX,NY), used if gridtype=0
400. 400.               # Grid spacing (DX,DY), used if gridtype=0
451737. 4519302.        # Center of the grid
5.0E11                  # Total Mass
1                       # Mass distribution model (0=from file, 1=Suzuki)
451737. 4519302. 0.0 # Coordinates of the vent (X,Y,Z)
18000.                  # Column height (a.s.l.)
36                      # Number of vertical source points
4. 1.                   # Suzuki coefficients
5000.                   # Diffusion coefficient
10                      # Number of loading thresholds
100. 200. 300. 400. 500. 600. 700. 800. 900. 1000. # Thresholds
10                        # Number of particles types
15.62e-6  1400 1.0  7.0   # Diameter, density, shape, wt%
31.25e-6  1400 1.0 10.0   # Diameter, density, shape, wt%
62.50e-6  1400 1.0 12.0   # Diameter, density, shape, wt%
125.0e-6  1700 1.0 21.0   # Diameter, density, shape, wt%
250.0e-6  1700 1.0 17.0   # Diameter, density, shape, wt%
500.0e-6  2500 1.0 10.0   # Diameter, density, shape, wt%
1.000e-3  2500 1.0  9.0   # Diameter, density, shape, wt%
2.000e-3  2500 1.0  8.0   # Diameter, density, shape, wt%
4.000e-3  2500 1.0  5.0   # Diameter, density, shape, wt%
8.000e-3  2500 1.0  1.0   # Diameter, density, shape, wt%
```

Table 3: Sample of file `sources.inp`, read by GENINP when flag SMODEL=0.

```
20                                # Number of sources (N)
451737.0 4519302.0  1000.0  0.0189  # X(1),Y(1),Z(1),Fract(1)
451737.0 4519302.0  2000.0  0.0219  # X(2),Y(2),Z(2),Fract(2)
451737.0 4519302.0  3000.0  0.0252  # ...
451737.0 4519302.0  4000.0  0.0290
451737.0 4519302.0  5000.0  0.0332
451737.0 4519302.0  6000.0  0.0378
451737.0 4519302.0  7000.0  0.0429
451737.0 4519302.0  8000.0  0.0484
451737.0 4519302.0  9000.0  0.0541
451737.0 4519302.0 10000.0  0.0601
451737.0 4519302.0 11000.0  0.0660
451737.0 4519302.0 12000.0  0.0717
451737.0 4519302.0 13000.0  0.0766
451737.0 4519302.0 14000.0  0.0802
451737.0 4519302.0 15000.0  0.0815
451737.0 4519302.0 16000.0  0.0796
451737.0 4519302.0 17000.0  0.0728
451737.0 4519302.0 18000.0  0.0591
451737.0 4519302.0 19000.0  0.0358
451737.0 4519302.0 20000.0  0.0052  # X(N),Y(N),Z(N),Fract(N)
```

Table 4: Sample of file `winds.dat`

```
10                      # Number of Z-levels (NLEV)
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  0.480 # 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 -0.097 -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  0.547 # 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 -0.567 -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
```

Table 5: Sample of file `grid.inp`

```
14                                     # Number of grid points
A01    455906.49   4525475.47          # Label( 1),  X( 1), Y( 1)
A02    461854.99   4521649.46          # Label( 2),  X( 2), Y( 2)
A03    459512.68   4521538.59          # Label( 3),  X( 3), Y( 3)
A04    459015.46   4516330.03          # Label( 4),  X( 4), Y( 4)
A05    457470.11   4516554.60          # Label( 5),  X( 5), Y( 5)
A06    469247.33   4531112.46          # Label( 6),  X( 6), Y( 6)
A07    465645.68   4526071.24          # Label( 7),  X( 7), Y( 7)
A08    471913.12   4524903.78          # Label( 8),  X( 8), Y( 8)
A09    460308.68   4521503.43          # Label( 9),  X( 9), Y( 9)
A10    461577.36   4522298.46          # Label(10),  X(10), Y(10)
A11    480443.45   4528884.87          # Label(11),  X(11), Y(11)
A12    475851.04   4526647.48          # Label(12),  X(12), Y(12)
A13    478214.55   4526670.95          # Label(13),  X(13), Y(13)
A14    464973.24   4532303.34          # Label(14),  X(14), Y(14)
```

Table 6: Sample of file `hazmap-dep.out` (flag OUTFMT=1)

```
0                                      # Mode
14                                     # Number of grid points
A01 455906.49 4525475.47     41.35     # Label( 1), X( 1), Y( 1), Load(1)
A02 461854.99 4521649.46    663.14     # Label( 2), X( 2), Y( 2), Load(2)
A03 459512.68 4521538.59    620.72     # Label( 3), X( 3), Y( 3), Load(3)
A04 459015.46 4516330.03    229.95     # Label( 4), X( 4), Y( 4), Load(4)
A05 457470.11 4516554.60    230.30     # Label( 5), X( 5), Y( 5), Load(5)
A06 469247.33 4531112.46     11.09     # Label( 6), X( 6), Y( 6), Load(6)
A07 465645.68 4526071.24    111.59     # Label( 7), X( 7), Y( 7), Load(7)
A08 471913.12 4524903.78    190.94     # Label( 8), X( 8), Y( 8), Load(8)
A09 460308.68 4521503.43    648.83     # Label( 9), X( 9), Y( 9), Load(9)
A10 461577.36 4522298.46    544.63     # Label(10), X(10), Y(10), Load(10)
A11 480443.45 4528884.87     50.48     # Label(11), X(11), Y(11), Load(11)
A12 475851.04 4526647.48     90.78     # Label(12), X(12), Y(12), Load(12)
A13 478214.55 4526670.95     95.01     # Label(13), X(13), Y(13), Load(13)
A14 464973.24 4532303.34      4.15     # Label(14), X(14), Y(14), Load(14)
```

Table 7: Format of a GRD file `hazmap.grd`.

```
NX   NY
XO   XF
YO   YF
MIN(VAL) MAX(VAL)
VAL(i,1)  ... ... i=1:NX
           ... ...
VAL(i,j)  ... ... i=1:NX
...        ... ...
VAL(i,NY) ... ... i=1:NX
```

Table 8: Sample of file `vset.out`

```
 10    50      # Number of particle types, Number of Z-levels
0.00000E+00 0.50000E+03 0.10000E+04 ... # Z-LEVELS   (i=1,50)
0.10324E-01 0.10418E-01 0.10513E-01 ... # V1(Z(i))   (i=1,50)
0.40473E-01 0.40856E-01 0.41248E-01 ... # V2(Z(i))   (i=1,50)
0.14985E+00 0.15148E+00 0.15314E+00 ... # V3(Z(i))   (i=1,50)
0.56111E+00 0.56910E+00 0.57728E+00 ... # V4(Z(i))   (i=1,50)
0.13913E+01 0.14158E+01 0.14410E+01 ... # V5(Z(i))   (i=1,50)
0.36853E+01 0.37587E+01 0.38345E+01 ... # V6(Z(i))   (i=1,50)
0.67938E+01 0.69353E+01 0.70815E+01 ... # V7(Z(i))   (i=1,50)
0.11013E+02 0.11282E+02 0.11561E+02 ... # V8(Z(i))   (i=1,50)
0.15574E+02 0.15955E+02 0.16349E+02 ... # V9(Z(i))   (i=1,50)
0.22025E+02 0.22563E+02 0.23121E+02 ... # V10(Z(i))  (i=1,50)
```

Table 9: Sample of file `grid.out` (with automatic grid generation)

```
22500                          # Number of grid points
00000   425662.00 4493227.00   # Label(1), X(1), Y(1)
00001   426012.00 4493227.00
00002   426362.00 4493227.00
00003   426712.00 4493227.00
00004   427062.00 4493227.00
00005   427412.00 4493227.00
00006   427762.00 4493227.00
00007   428112.00 4493227.00
00008   428462.00 4493227.00
00009   428812.00 4493227.00
00010   429162.00 4493227.00
00011   429512.00 4493227.00
00012   429862.00 4493227.00
00013   430212.00 4493227.00
00014   430562.00 4493227.00
00015   430912.00 4493227.00
00016   431262.00 4493227.00
00017   431612.00 4493227.00
00018   431962.00 4493227.00
00019   432312.00 4493227.00
00020   432662.00 4493227.00
00021   433012.00 4493227.00
00022   433362.00 4493227.00
00023   433712.00 4493227.00
```

Table 10: Sample of file `hazmap-spe.out`

```
14   10     # Number of grid points, Number of particle types
A01 0.0000 0.0000 0.0039 0.1948 0.2421 0.1812 ... # Sect.1
A02 0.0000 0.0000 0.0013 0.0224 0.0445 0.0766 ... # Sect.2
A03 0.0000 0.0000 0.0007 0.0295 0.0527 0.0847 ... # Sect.3
A04 0.0000 0.0000 0.0006 0.0256 0.0489 0.0857 ... # Sect.4
A05 0.0000 0.0000 0.0004 0.0299 0.0559 0.0927 ... # Sect.5
A06 0.0000 0.0000 0.1301 0.3347 0.2912 0.1273 ... # Sect.6
A07 0.0000 0.0000 0.0185 0.0945 0.1421 0.1548 ... # Sect.7
A08 0.0000 0.0000 0.0125 0.0547 0.1054 0.1626 ... # Sect.8
A09 0.0000 0.0000 0.0009 0.0261 0.0486 0.0805 ... # Sect.9
A10 0.0000 0.0000 0.0016 0.0281 0.0535 0.0859 ... # Sect.10
A11 0.0000 0.0000 0.0215 0.1501 0.2282 0.2297 ... # Sect.11
A12 0.0000 0.0000 0.0179 0.1002 0.1772 0.2318 ... # Sect.12
A13 0.0000 0.0000 0.0129 0.0929 0.1710 0.2343 ... # Sect.13
A14 0.0000 0.0001 0.1824 0.4108 0.2564 0.0677 ... # Sect.14
```