



TephraProb

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User manual

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Contents

List of Figures	ii
List of Tables	ii
1 Introduction	1
2 Installation and requirements	1
3 Getting started	1
4 Input parameters	1
4.1 Calculation grid	3
4.1.1 Grid	3
4.1.2 Points	5
4.2 Wind conditions	5
4.2.1 ERA–Interim	6
4.2.2 Post–processing and analyzing wind conditions	7
4.3 Global Volcanism Program	8
5 Probabilistic eruption scenarios	9
5.1 Run parameters	10
5.2 Structure of the output	14
5.3 Running Tephra2	15
5.3.1 Single–CPU machine	15
5.3.2 Computer cluster	15
6 Post–processing	15
6.1 Probability maps	16
6.2 Hazard curves	16
6.3 Probabilistic isomass maps	17
7 Displaying and exporting results	17
7.1 Distributions of ESP	17
7.2 Probability maps	17
7.3 Probabilistic isomass maps	18
7.4 Hazard curves	18
Examples of empirical parameters for Tephra2	I
Description of the files	I
References	II
License	V

List of Figures

1	Workflow of <i>TephraProb</i>	3
2	Cygwin requirements	4
3	Main interface	4
4	Calculation grids	5
5	Points of interest	6
6	Download wind data	7
7	Wind analysis	8
8	Global Volcanism Program	9
9	Algorithms of probabilistic eruption scenarios	11

List of Tables

1	Main functionalities of <i>TephraProb</i>	2
2	Probabilistic eruption scenarios	10
3	Empirical parameters for selected eruptions constrained by deposit inversion using Tephra2.	I

1 Introduction

The *TephraProb* package offers an integrated environment to produce probabilistic hazard assessments for tephra fallout through a user-friendly *Matlab* interface and using the advection-diffusion model Tephra2 (Bonadonna et al, 2005). The package can be divided in three main sections including modules to:

- Retrieve, process and analyse the input data required for probabilistic assessments of tephra fallout (i.e. calculation grid, wind conditions, eruptive history);
- Create distributions of Eruption Source Parameters (ESP) for various types of eruptions and various probabilistic eruption scenarios;
- Post-process the results and compile comprehensive outputs (i.e. probability maps, hazard curves, probabilistic isomass maps).

Figure 1 summarizes the workflow implemented in *TephraProb*. This manual provides an in-depth look into the functionalities of the *TephraProb* package at every step of the compilation of a comprehensive probabilistic hazard assessment for tephra accumulation. Note that an online video tutorial is available [here](#).

2 Installation and requirements

The *TephraProb* package is written in Matlab and can therefore run on any operative system (OS). The minimum Matlab version required is R2011b (i.e. 7.13). The Tephra2 model runs under Unix, and in order to run on Windows, it is necessary to download and install *Cygwin*¹. Two necessary options are required when installing *Cygwin*, namely the *GCC* compiler and the *Make* utility. Make sure to install dependencies according to Figure 2. Finally, the access to ECMWF requires *Python*. By experience, we had less problems with *Python 2.7* than *Python 3.5*.

3 Getting started

The **TephraProb** folder should be placed on the hard drive and not be moved in order to preserve consistent links to files within projects. Six sub folders are contained within the main folder:

- CODE/**: Contains the scripts used in the TephraProb package
- CURVES/**: Output folder for the hazard curves
- GRID/**: Output folder for the grids
- MODEL/**: Contains the Tephra2 model
- RUNS/**: Contains all output files of projects
- WIND/**: Output files for wind files

The TephraProb folder also contains a file named **tephraProb.m**, which is the main GUI of *TephraProb*. To start *TephraProb*, navigate to the *TephraProb* folder within *Matlab* and type:

```
>> tephraProb
```

The main interface is shown in Figure 3, and the main functionalities are summarized in Table 1.

4 Input parameters

¹<https://www.cygwin.com>

File	Load	Load a .mat project file
	Preferences	Set main preferences of the <i>TephraProb</i> package
Input	Grid	Create, plot, load calculations grids
	Points	Set points of interests, which can be used as calculation points or as reference points for compiling hazard curves
	Wind	Writes the ECMWF API Key received from registration Install the necessary Python libraries Download wind data from the NOAA NCEP/NCAR Reanalysis dataset (Kalnay et al, 1996) Download wind data from the ECMWF Era-Interim dataset (Dee et al, 2011) Convert NetCDF files to ascii wind profiles Statistical analyses of wind conditions
	GVP	Access and analyze the eruptive history of a volcano from the Global Volcanism Program (GVP) of the Smithsonian Institution (Simkin and Siebert, 1994)
Scenarios	Sub-Plinian/Plinian	Create eruption scenarios for sub-Plinian/Plinian eruptions
	Vulcanian	Create eruption scenarios for Vulcanian eruptions
Post-processing	Probability calculations	Post-processing of the output to produce probability maps
	Hazard curves	Post-processing of the output to produce hazard curves
	Probabilistic isomass maps	Compile probabilistic isomass maps from probability matrices
	Display figure	Display any type of figure created during the generation of ESPs (e.g. histograms of each separate ESP)
Display	Probability maps	Display probability maps using a background from <i>Google Maps</i>
	Probabilistic isomass maps	Display probabilistic isomass maps using a background from <i>Google Maps</i>
	Hazard curves	Display hazard curves

Table 1: Summary of the functionalities of *TephraProb* as displayed on the main interface.

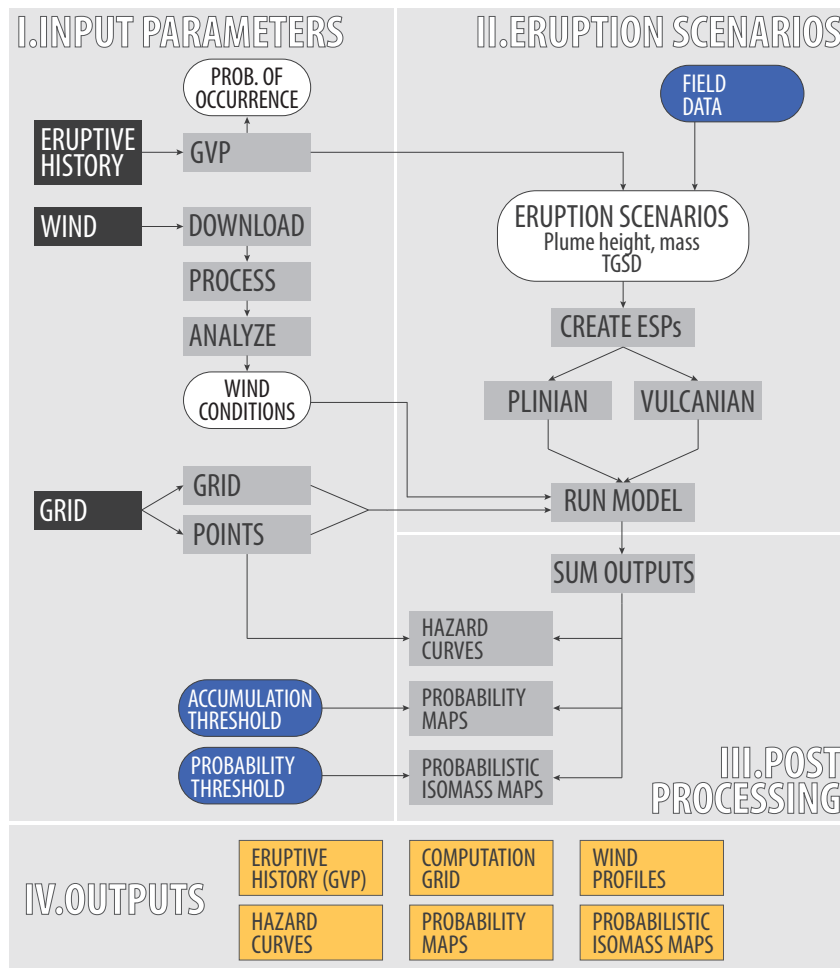


Figure 1: Workflow implemented in *TephraProb*, including 3 main sections to i) access and pre-process the necessary input data, ii) run a large range of probabilistic eruption scenarios and iii) post-process the model outputs into a comprehensive set of probabilistic tools.

4.1 Calculation grid

TephraProb relies on the advection–diffusion model *Tephra2* (Bonadonna and Houghton, 2005), which requires a set of calculation points or a calculation grid on which tephra accumulation will be computed. Probabilistic hazard assessments are typically performed on a grid of points in order to produce probability maps, which result in long-computation times. If this approach is viable when a cluster of computer is available, the computational cost is generally too large for a single CPU. For this reason, *TephraProb* allows to perform probabilistic hazard assessments on a few selected points only and can work with multiple cores CPUs. Although this approach does not allow to compile probabilistic hazard maps, it makes possible to produce hazard curves.

Tephra2 requires points using the Universal Transverse Mercator (UTM) projection, which divides the earth into sixty zones comprised between 80°S and 84°N each 6° in latitude². Although coordinates are continuous within a given zone, they shift when crossing zones laterally or when passing the equator. The *TephraProb* package allows to correct this shift in zones in order to preserve the continuity of the coordinates. The distortion induced is considered negligible compared to the distance over which *Tephra2* is valid.

4.1.1 Grid

Figure 4 shows the GUI to set the grid parameters. Required parameters are:

Minimum easting: UTM coordinate of the westernmost boundary of the grid

Maximum easting: UTM coordinate of the easternmost boundary of the grid

Minimum northing: UTM coordinate of the southernmost boundary of the grid

²https://en.wikipedia.org/wiki/Universal_Transverse_Mercator_coordinate_system

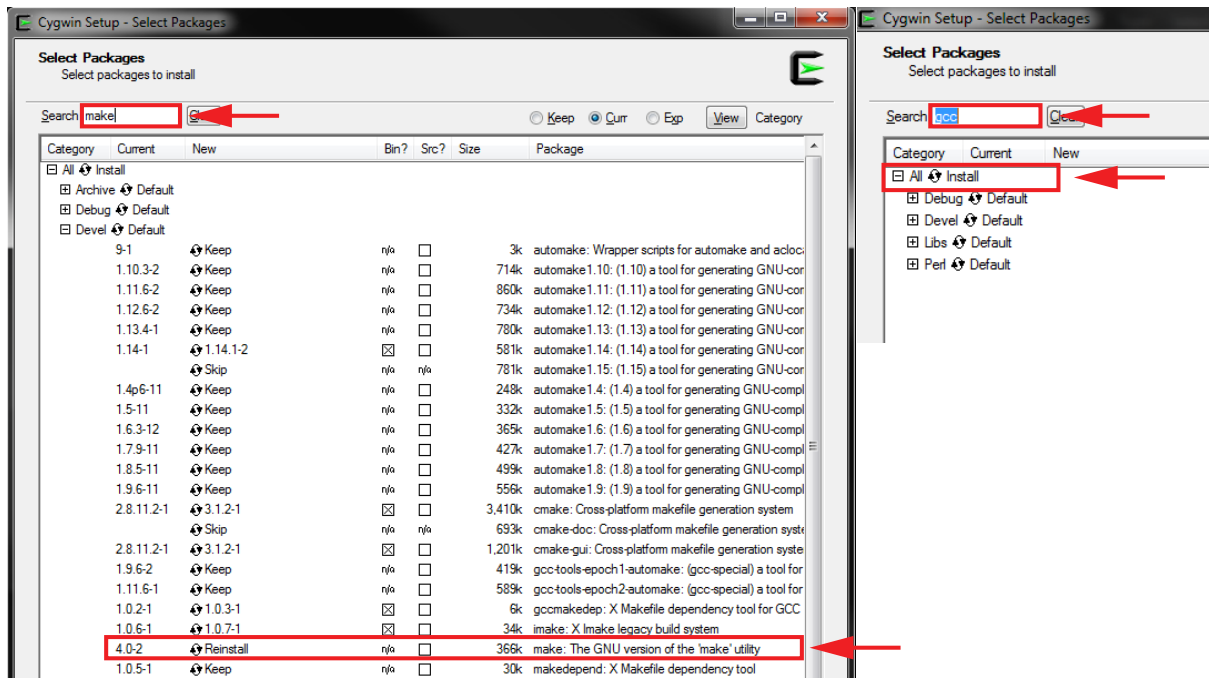


Figure 2: Additional packages required during the *Cygwin* install. Make sure to install the *Make* utility (left) and the *GCC* compiler (right).

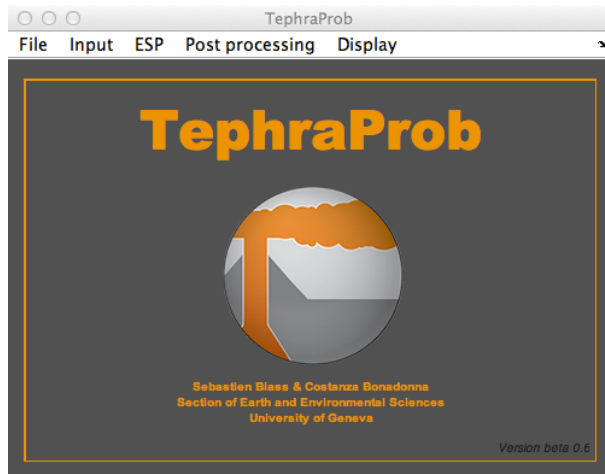


Figure 3: Main interface of the *TephraProb* package.

Maximum northing: UTM coordinate of the northernmost boundary of the grid

UTM zone: UTM zone number (i.e. without the corresponding letter). The zone number should be ≥ 0 in the northern hemisphere and < 0 in the southern hemisphere. Enter one zone if the grid is contained within a single UTM zone, two if it crosses either two lateral zones or the equator and four if it crosses both. In all cases, the boundary coordinates entered above must correspond the respective zones.

Vent zone: UTM zone of the eruptive vent. Used to define the continuity of coordinates

Grid resolution: The resolution of the grid, in metres

Grid name: The name of the generated grid

Once filled, it is possible to plot the extent of the grid using the **Plot Grid** button. The **Generate grid** button generates the grid in the *GRID/* folder. Each grid consists in seven files:

_lat.dat: Latitude of the points of the grid in a matrix format

_lon.dat: Longitude of the points of the grid in a matrix format

_utm.dat: Easting of the points of the grid in a matrix format

Figure 4: Interface for generating calculation grids.

- `_utmy.dat`: Northing of the points of the grid in a matrix format
- `.dat`: Altitude of the points of the grid in a matrix format
- `.mat`: Matlab structure containing the parameters of the grid
- `.utm`: 3-columns grid for calculation with Tephra2

It is possible to load a previously created grid by using the Load button, in which case it is required to locate the `.mat` grid file.

4.1.2 Points

The *Points* function allows to i) create calculation points to produce probabilistic hazard assessments consisting of hazard curves only when no cluster of computers is available and ii) to define points of interest to calculate hazard curves. Figure 5 shows the main interface to define these points, which should be entered in latitude/longitude coordinates in decimal degrees. Additionally, the vent UTM zone must be specified, following the same shape as for the grid (i.e. zone without a letter, negative in southern hemisphere). It is possible to plot the points and to load previously created points.

The point files are saved in the *GRID/* folder and consist of two files including:

- `.points`: Ascii file used for the calculation of hazard curves (see Section 6.2)
- `.utm`: 3-columns grid for calculation with Tephra2

4.2 Wind conditions

Wind conditions are an important parameter of any tephra dispersal and sedimentation model. In addition, probabilistic hazard assessments require to access datasets spanning over at least one decade in order to capture the aleatoric nature of wind conditions. As a result, most hazard assessment for tephra rely on Reanalysis datasets, amongst which the two most frequently used include the NOAA NCEP/NCAR Reanalysis 1 (Kalnay et al, 1996), the NCEP-DOE Reanalysis 2 (Kanamitsu et al, 2002) and the ECMWF Era-Interim (Dee et al, 2011). The *TephraProb* package offers to access these two datasets through GUIs. However, the ECMWF Era-Interim requires an additional distribution of Python.

Both NOAA datasets provides wind conditions on a 2.5° resolution grid and at 17 pressure levels. A maximum of 4 wind profiles are available everyday extracted at 00, 06, 12 and 18 h UTC. The NOAA

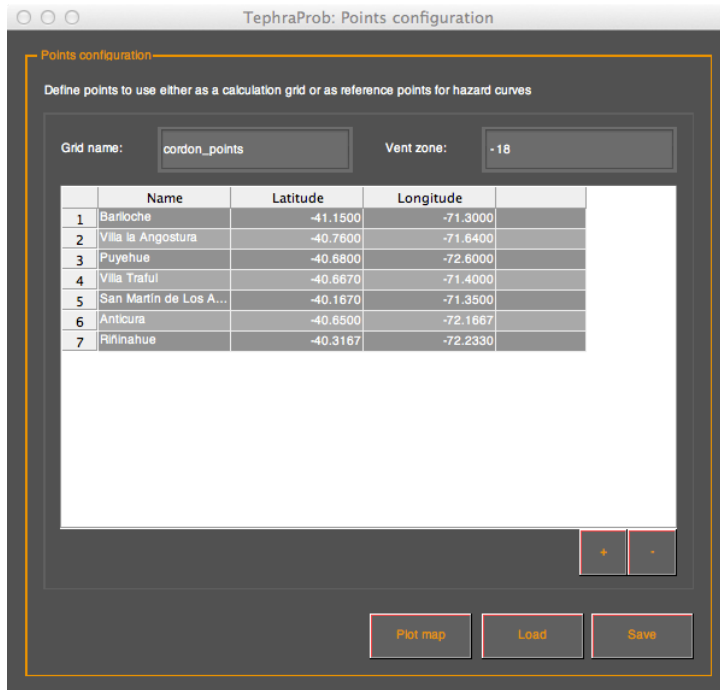


Figure 5: Interface for generating points of interest.

NCEP/NCAR Reanalysis 1 dataset contains data since 1948/01/01³ and the NCEP-DOE Reanalysis 2 since 1979/01/01⁴. The ERA-Interim dataset also provide up to 4-daily profiles on a minimum resolution of 0.25° from 1979/01/01 to present, and contains 37 pressure levels⁵.

Figure 6 shows the *TephraProb* interface to download wind data. The *TephraProb* package downloads files in the NetCDF format and converts them into three columns ascii files including altitude, wind direction (i.e. the direction in which the wind blows) and wind velocity. Wind files are downloaded in the WIND folder inside the root *tephraProb* folder. Each new wind project contains a folder named **ascii** where the ascii wind profiles are generated. The access to the NOAA and the ECMWF databases are different. In the case of NOAA, worldwide NetCDF files are downloaded for each requested year into the folder WIND/_ReanalysisX_Rawdata/ (where X is either 1 or 2), and the extraction of the zone of interest is done at post-processing. Although the downloading time is relatively long, these worldwide files are preserved, so if a future project requires the same years but a different zone of interest, no downloading will be necessary. In the case of the ECMWF dataset, separate NetCDF files are downloaded for the zone of interest into the folder WIND/project/nc/.

Since reanalysis datasets are gridded, *TephraProb* interpolates wind conditions to the vent coordinates. The **Subset** extends the zone of interest around the vent and defines the number of points used in the interpolation. A **Subset**= 2 extends by 2 grid cell in each direction, resulting in an interpolation performed on a 4 × 4 grid. The interpolation method are those implemented in Matlab (see help for the *interp2* function).

4.2.1 ERA-Interim

If downloading ERA-Interim for the first time, a few installation steps are necessary:

- Create an account on the ECMWF website: <https://apps.ecmwf.int/registration/>
- Login to the ECMWF website : <https://apps.ecmwf.int/auth/login/>
- Retrieve an API key: <https://api.ecmwf.int/v1/key/>
- Accept the license: <http://apps.ecmwf.int/datasets/licences/general/>
- From the main *TephraProb* interface, choose *Input > Wind > Set ECMWF API Key* and enter the newly received API key in the text box. This creates a file called **.ecmwfapirc** (i.e. a text file

³<http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html>

⁴<https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.html>

⁵<http://www.ecmwf.int/en/forecasts/datasets/era-interim-dataset-january-1979-present>

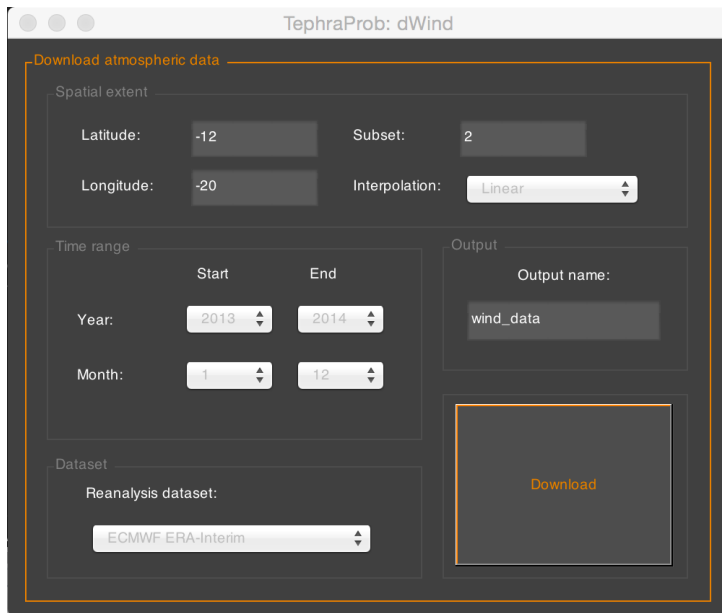


Figure 6: Interface to download wind data.

without extension and whose name begin with a dot) placed in the **HOME** folder of your computer (on Windows: `c:/Users/username/`; on Unix: `/home/username/`)

- *Input > Wind > Install ECMWF Libraries* to install the Python libraries necessary to retrieve data in batch ⁶. The libraries are located in the folder `CODE/ecmwf-api-client-python`.

Hoping that everything compiled without error, it is now possible to download wind data from the ERA-Interim dataset by choosing the *Download ECMWF wind* function in the main *TephraProb* interface. One known issue can occur at this point and display the following message:

```
File "setup.py", line 12, in <module>
    from setuptools import setup, find_packages
ImportError: No module named setuptools
```

In this case, simply install the `setuptools` using the following command in the terminal:

```
sudo apt-get install python-setuptools
```

4.2.2 Post-processing and analyzing wind conditions

Once datasets of either dataset finished downloading, run the *Process wind* tool to convert the NetCDF files into ascii wind profiles. This process also creates a file called `wind.mat` file in the `WIND/yourwindproject/` folder. Run next the *Analyze wind* tool to visualize the wind conditions. When asked to load a wind project, select the newly created `wind.mat` file and wait for the interface to appear (Fig. 7). The *Wind analysis* window allows to plot wind conditions either as profiles of velocity and direction with height or as wind roses for a given altitude. It is possible to plot wind directions either as the provenance or the direction of the flow (i.e. provenance + 180°). To plot the data in the axes of the GUI, use the **Plot** button. To export the plot for saving and editing, use the **Zoom/export** button.

Wind profiles Two main options exist to plot wind profiles, i.e. *Averaged* or *Separate*. In the case of *Averaged*, the profiles are plot either as the median \pm interquartile range (i.e. 25th and 75th percentiles of the population) or as the mean \pm standard deviation, depending on the option chosen in the *Average type* box. It is possible to plot such profiles either the entire population or sub-populations based on the year or the month. In both cases, it is possible to select more than one entry in the list shown in the *Subset* box. In the case of *Separate*, it is possible to show the median/mean of separate years or months superimposed on the same axes. This options is useful to assess potential climatic effects with a long period (e.g. El Nino) or a potential seasonality effect. It is also possible to plot separate wind profiles for a given date.

⁶<https://software.ecmwf.int/wiki/display/WEBAPI/Accessing+ECMWF+data+servers+in+batch>

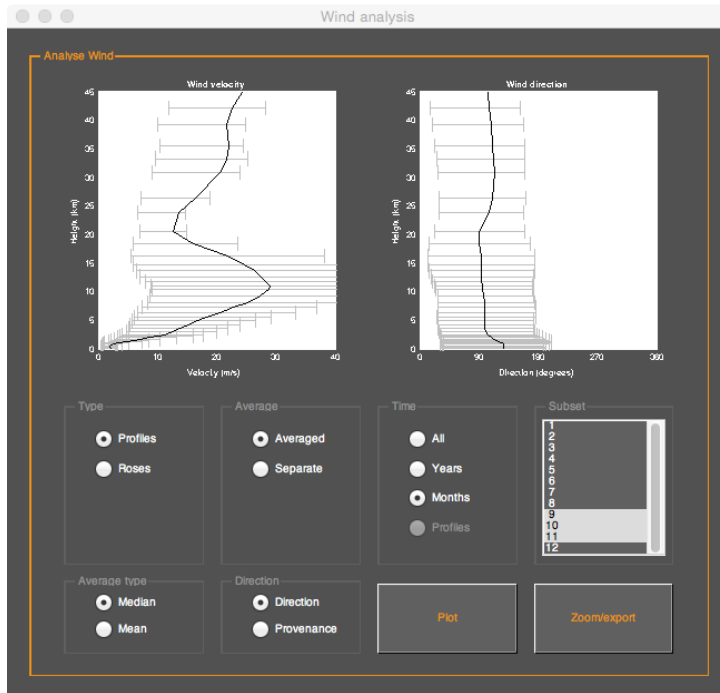


Figure 7: Interface to analyze wind conditions

Wind roses When the *Roses* option of the *Type* box is selected, a new box named *Altitude* appears and displays the median altitude of the pressure levels reported in the Reanalysis datasets. For a given altitude, it is possible to plot either the entire dataset, separate years or separate months. In the cases of years and months, it is also possible to select more than one entry in the list of the *Subset* box.

4.3 Global Volcanism Program

In volcanology, hazard assessments are based upon the assumption that future activity will be similar to past activity or will follow a present trend, which implies a necessity to assess the past eruptions in order to frame the most likely eruption scenarios. The field characterization of eruption is a long and expensive process, and a single field campaign allows the study of a typical maximum of a couple of eruption. Eruptions scenarios are generally drawn around a few studied eruptions accounting for specific eruptive styles. However, the philosophy behind the *TephraProp* package is that a rough hazard assessment is better than nothing. For this reason, the package contains a module to access eruption data from the Global Volcanism Program of the Smithsonian Institute⁷ (GVP; Simkin and Siebert, 1994; Siebert et al, 2010) in order to estimate the eruptive history of a given volcano based on the Holocene record when i) a global estimate of the eruptive magnitude and styles are required or ii) when additional information is required to extend eruptive scenarios around studied eruptions.

Figure 8 shows the main interface of the GVP tool. In the GVP database, each volcano is referenced by a *volcano number* which can be found on the GVP website. Once identified and entered in Figure 8, click the **Access** button to retrieve the data.

Once the data are retrieved, two main options are available for plotting the eruptive history, either as histogram per VEI class or as cumulative number of eruption through time. The **VEI** box allow to select eruptions of given VEI classes. Often, due to the lack of field studies, the VEI can be unspecified (*U* in Fig. 8), or the VEI is sometime considered as "other" (*O* in Fig. 8). The **Confirmed** box allows to select either confirmed or unconfirmed eruptions, and the **Evidence** box gives the option to select eruptions dated either by the historical record, by tephrochronology or radiocarbon dating. Refer to Simkin and Siebert (1994) and Siebert et al (2010) for further descriptions of the GVP database.

Plots of cumulative number of eruptions through time make possible to identify segments characterized by different slopes, themselves indicating apparent changes in eruption rates. However, as discussed by Siebert et al (2010), these artefacts reflect the completeness of the eruptive history, and typically include an oldest flat segment where only large eruptions are preserved in the geological record, a middle

⁷<http://www.volcano.si.edu>

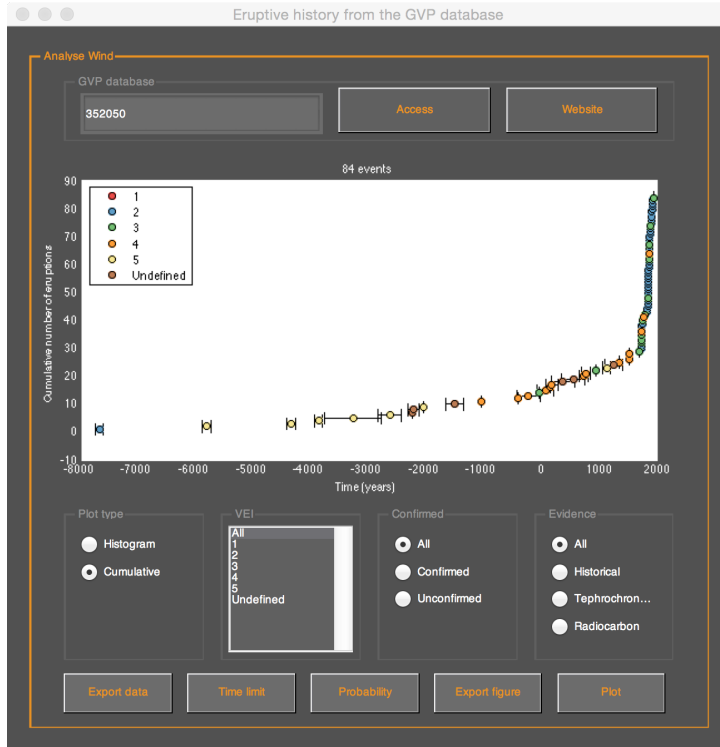


Figure 8: Interface to analyze the eruptive history from the GVP database.

steeper segment where the geological record is complete and a steep recent segment constituting the historical record, in which most small eruptions are preserved.

If we assume that the considered eruptions are independent events, i.e. that the probability of an event occurring in the future does not depend on previous events, it is possible to estimate a probability of eruption in a given time window by modelling them as a Poisson process (e.g. Biass and Bonadonna, 2013; Dzierma and Wehrmann, 2010; Borradaile, 2003). We aim to quantify the probability that a repose interval T is smaller or equal to an arbitrary time window t :

$$F(t) = P(T \geq t)$$

which, in the simplest case of a Poisson process, results in an exponential distribution:

$$F_{exp}(t) = 1 - e^{-\lambda t},$$

where t is a forecasting window (years) and λ is the eruption rate (number of eruptions per year). As discussed by Biass and Bonadonna (2013), λ must be defined on a period where the eruptive history is judged complete, which can vary when eruption of different sizes are considered.

It is possible to estimate the probability of occurrence of an eruption within a given time interval directly in *TephraProb*:

- From the plot of cumulative number of eruption through time, identify the period where the record is complete. Note that this period of completeness might vary depending on the VEI;
- Use the **Time limit** button and enter the completeness of your dataset. Click the **Plot** button to actualize the plot;
- Click on the **Probability** button to visualize the variation of the eruption probability through time.

5 Probabilistic eruption scenarios

Probabilistic analyses in hazard assessment help investigate both parts of the geological record that are not accessible or removed as well as eruptive events that have not happened yet but potentially could in the future. Probabilistic eruption scenarios are based upon these considerations and aim, through

Eruption type	Scenario	Acronym	Event ^a		ESP		Wind	
			Single	Multiple	Fixed	Variable	Fixed	Variable
Plinian^b	Eruption Range Scenario	ERS	✓			✓		✓
	One Eruption Scenario	OES	✓		✓			✓
	Wind Range Scenario	WRS	✓			✓		✓ ^c
	Fixed Date Scenario	FDS	✓			✓	✓	
Vulcanian	Eruption Range Scenario	V-ERS	✓			✓		✓
	LL Eruption Range Scenario	V-LLERS		✓		✓		✓
	One Eruption Scenario	V-OES	✓		✓			✓
	Wind Range Scenario	V-WRS	✓			✓		✓ ^c
	Fixed Date Scenario	V-FDS	✓			✓	✓	

^a Modelling of *single* single sustained eruptions or *multiple* repetitive ash emission (e.g. long-lasting Vulcanian cycles)

^b Plinian scenarios are long-lasting when the eruption duration is longer than the wind sampling interval

^c Within a pre-defined radial sector around the volcano

Table 2: Summary of the probabilistic eruption scenarios for sub-Plinian/Plinian (P-type) and Vulcanian (V-type) types of eruptions implemented in *TephraProb*. Figure 9 summarizes the implementation of the main eruption scenarios.

Monte Carlo simulations (e.g. Hurst and Smith, 2004), to account for the aleatoric uncertainties of both eruptive intensity and wind conditions. The *TephraProb* package was designed to offer the largest possible flexibility to model eruptions in a stochastic way and includes a wide range of eruptive scenarios designed for both sub-Plinian/Plinian and Vulcanian eruptions, hereafter referred to as *P-type* and *V-type* scenarios.

Table 2 summarizes the main eruption scenarios and Figure 9 presents their implementation in *TephraProb*, which are based upon or developed after Bonadonna (2006) and (Biass et al, 2014). Two main scenarios are implemented and include the One Eruption Scenario (OES), in which ESPs are deterministically fixed and wind conditions are variable, and the Eruption Range Scenario (ERS), in which both ESPs and wind conditions are stochastically sampled at each run. The Wind Range Scenario (WRS) and Fixed Date Scenarios (FDS) are used to constrain wind conditions and can be both applied using sets of ESPs deterministically fixed or stochastically sampled. The WRS constrains the sampling of wind profiles within a range of directions and is designed to assess the hazard at specific sites considering a worst-case wind scenario. The FDS uses wind conditions at a given date and is useful to re-assess witnessed eruptions.

In *TephraProb*, there are main differences in modelling P- and V-types of eruptions. Firstly, for P-type eruptions, in the case the eruption duration is longer than the period of validity of single wind profiles (i.e. 6 hours for most Reanalysis datasets), all eruption scenarios can be modelled as *long-lasting*, in which case the prefix *LL-* is added. If this option is adopted, one eruption is sliced in 6 hours parts during which ESPs are assumed constant, and each part is a different run of *Tephra2*. The final accumulation of such an eruption is calculated as the sum of the contributions of each part. Finally, the Multiple Eruptions Scenario (MES) assesses the contribution of several eruptions modelled as any scenario described above (e.g. Bonadonna et al, 2005)

Secondly, Vulcanian eruptions differ from sub-Plinian and Plinian eruptions on two main aspects. Firstly, long-lasting Vulcanian eruptions consider Vulcanian eruptive cycles consisting of repetitive emissions of ash, called here *explosions* and themselves considered thermal, i.e. instantaneous. The total accumulation of one eruption consists of the sum of the contribution of each explosion. Secondly, the mass of one explosion is directly related to the plume height by the thermal equation of Bonadonna et al (2002a):

$$H_{VP} = 55M^{0.25} + H_V$$

where H_{VP} is the plume height (*m* a.s.l.), M is the plume mass (*kg*) and H_V the vent height (*m* a.s.l.).

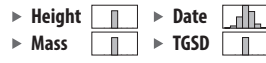
5.1 Run parameters

The ESP menu of the main interface (Fig. 3) consists in two main functions, namely *sub-Plinian/Plinian* and *Vulcanian*. Both functions display a set of required variables to run probabilistic eruption scenarios. Each parameter is described in detail below, where it is specified in brackets whether it is specific of P or V type scenarios.

General: General parameters of the run

Plinian One Eruption Scenario (OES)

User input:



For each run i in a total number of runs n_i


- Sample $Date_i \rightarrow Get Wind_i$
- Run model $\rightarrow Output_i$
- Update counter $\rightarrow i = i + 1$
- Next run

Plinian Eruption Range Scenario (ERS)

User input:

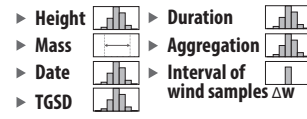


For each run i in a total number of runs n_i

- Sample $Date_i \rightarrow Get Wind_i$
- Sample $Height_i \rightarrow Calculate MER_i^a$
- Sample $Duration_i \rightarrow Calculate Mass_i$
- Sample $TGSD_i, Aggregation_i$
- Aggregate $TGSD_i \rightarrow TGSD_i^*$
- Test if $Mass_i$ within $Mass$ 
 - YES
 - Run model $\rightarrow Output_i$
 - Update counter $\rightarrow i = i + 1$
 - Next run
 - NO
 - Restart sampling

Plinian Long-Lasting ERS (LL-ERS)


User input:



For each run i in a total number of runs n_i

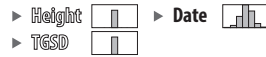
- Sample $Date_i \rightarrow Get Wind_i$
- Sample $Duration_i$
- Split $Duration_i$ in n_i simulations of $Duration_{ij} \leq \Delta w$
- Sample $TGSD_i, Aggregation_i$
- Aggregate $TGSD_i \rightarrow TGSD_i^*$

For each simulation j in a total number of simulations n_j

- Get $Date_{ij} \rightarrow Wind_{ij}$
- Sample $Height_{ij} \rightarrow MER_{ij}^a$
- Get $Duration_{ij} \rightarrow Mass_{ij}$
- Test if sum ($Mass_{ij}$) within $Mass$ 
 - YES
 - Run model $\rightarrow Output_j$
 - Update counter $\rightarrow i = i + 1$
 - Next run
 - NO
 - Restart sampling

Vulcanian One Eruption Scenario (V-OES)

User input:



- Calculate $Mass^a$

For each run i in a total number of runs n_i

- Sample $Date_i \rightarrow Get Wind_i$
- Run model $\rightarrow Output_i$
- Update counter $\rightarrow i = i + 1$
- Next run

Vulcanian Eruption Range Scenario (V-ERS)

User input:



For each run i in a total number of runs n_i

- Sample $Date_i \rightarrow Get Wind_i$
- Sample $Height_i$
- Calculate $Mass_i^a$
- Sample $TGSD_i, Aggregation_i$
- Aggregate $TGSD_i \rightarrow TGSD_i^*$
- Run model $\rightarrow Output_i$
- Update counter $\rightarrow i = i + 1$
- Next run

Vulcanian Long-Lasting ERS (V-LLERS)

User input:






For each run i in a total number of runs n_i

- Sample $Date_i \rightarrow Get Wind_i$
- Sample $Duration_i$
- Sample $TGSD_i, Aggregation_i$
- Sample $Repose interval RI_{i,j}$
- Aggregate $TGSD_i \rightarrow TGSD_i^*$

While the sum of repose intervals $RI_{ij} \leq Duration_i$

- Get $Date_{ij} \rightarrow Wind_{ij}$
- Sample $Height_{ij}$
- Calculate $Mass_{ij}^a$
- Run model $\rightarrow Output_{ij}$
- Sample $Repose interval RI_{ij}$
- Update counter $\rightarrow j = j + 1$
- Update counter $\rightarrow i = i + 1$
- Next run

Input types	Variable types	Action types
 Single value	Height Input	Sample Action
 Distribution known a priori	Date_i Temporary	\rightarrow Chain step
 Range	Mass_i TEPHRA2	if sum Conditional

^a Mass of a thermal with the method of Bonadonna et al. (2002)

Figure 9: Algorithms used to generate ESPs for the main eruption scenarios implemented in *TephraProb*. The top three algorithms refer to sub-Plinian/Plinian types of eruptions. The bottom three algorithms are designed for Vulcanian type of eruptions.

-
- run_name:** Run name, with no space or special character (P,V)
 - out_name:** Generic name of output files, with no space or special character (P,V)
 - grid_pth:** Path to the *.utm grid file, expressed as a relative path from the root *TephraProb* folder (P,V)
 - wind_pth:** Path to the folder containing the .gen wind files, expressed as a relative path from the root *TephraProb* (P,V) folder

Vent: Vent parameters

- volcano_name:** Name of the volcano (P,V)
- vent_easting:** UTM easting of the vent (P,V)
- vent_northing:** UTM northing of the vent (P,V)
- vent_zone:** UTM zone of the vent (P,V)
- vent_ht:** Altitude of the vent (*m a.s.l.*) (P,V)

Eruption parameters: Ranges of eruption source parameters (ESPs)

- min_ht:** Minimum plume height (*m a.s.l.*) (P,V)
- max_ht:** Maximum plume height (*m a.s.l.*) — enter **min_ht** = **max_ht** for OES (P,V)
- min_mass:** Minimum mass (*kg*) (P)
- max_mass:** Maximum mass (*kg*) — enter **min_mass** = **max_mass** for OES (P)
- min_ri:** Minimum repose interval (*hours*) (V)
- max_ri:** Maximum repose interval (*hours*) — enter **min_ri** = **max_ri** for short-lasting Vulcanian scenarios, where **min_ri** > **max_dur** (V)
- min_dur:** Minimum duration (*hours* for P-type, *days* for V-type) (P,V)
- max_dur:** Maximum duration (*hours* for P-type, *days* for V-type) (P,V)
- constrain:** Boolean 0/1. If 0, plume height and erupted mass are sampled independently. If 1, only combinations of plume height, wind speed, MER calculated with Degruyter and Bonadonna (2012) and eruption duration resulting in a mass comprised in the **min_mass**–**max_mass** range are selected — enter 0 for OES (P)

Wind: Parameters of the wind population

- nb_wind:** Number of wind profiles in the wind population. Reducing this number will reduce the size of the wind profiles to use, and thus the size of the wind population (P,V)
- wind_start:** Date string of the first wind profile of the win population (e.g. 01-Jan-2001 00:00:00) (P,V)
- wind_per_day:** Number of wind profiles per day (typically 4, i.e. 6 hours for most Reanalysis datasets) (P,V)
- seasonality:** Boolean 0/1. If enabled, the code will perform three runs including i) all wind profiles, ii) wind profiles of the rainy season and iii) wind profiles of the dry season (P,V)
- wind_start_rainy:** Beginning month of the rainy season, used if **seasonality** = 1 (P,V)
- wind_start_dry:** Beginning month of the dry season, used if **seasonality** = 1 (P,V)
- constrain_eruption_date:** Boolean 0/1. If enabled, constrain the eruption start date for Fixed Date Scenarios (P,V)
- eruption_date:** Eruption start date (e.g. 01-Jan-2001 00:00:00), used if **constrain_eruption_date** = 1 (P,V)
- constrain_wind_dir:** Boolean 0/1. If enabled, constrain the sampling of wind profiles within a predefined range for Wind Range Scenarios (P,V)
- min_wind_dir:** Minimum wind direction (i.e. provenance + 180°), used if **constrain_wind_dir** = 1 (P,V)

-
- max_wind_dir:** Maximum wind direction (i.e. provenance + 180°), used if **constrain_wind_dir** = 1 (P,V)
- trop_height:** Tropopause height (*m.a.s.l.*), used to calculate the MER with the method of Degruyter and Bonadonna (2012) if **constrain** = 1. Note that the tropopause height varies with latitude!⁸ (P,V)

TGSD: Parameters of the total grain-size distribution

- max_phi:** Maximum ϕ range (i.e. coarsest end of the TGSD) (P,V)
- min_phi:** Minimum ϕ range (i.e. finest end of the TGSD) (P,V)
- min_med_phi:** Minimum median ϕ (P,V)
- max_med_phi:** Maximum median ϕ (P,V)
- min_std_phi:** Minimum $\sigma\phi$ (P,V)
- max_std_phi:** Maximum $\sigma\phi$ (P,V)
- min_agg:** Minimum empirical aggregation parameter (0–1). *TephraProb* accounts for aggregation using the empirical method of Bonadonna et al (2002a), in which a mass proportion equal to the empirical aggregation parameter is removed from the fine fraction of the TGSD. The fine fraction is defined as all diameters finer or equal than **MAX_DIAM**. The fraction of fine material removed is equally redistributed in bins ranging from -1ϕ to **MAX_DIAM**. (P,V)
- max_agg:** Maximum empirical aggregation parameter (0–1) (P,V)
- max_diam:** The maximum diameter affected by aggregation processes. Enter **5** to consider the aggregation of material < 63 microns (e.g. PC1, PC2, AP1) or **4** to consider the aggregation of material < 125 microns (e.g. AP2, AP3) (P,V)

RUN: Run parameters

- long_lasting:** Choose if the long-lasting strategy described above is applied (0: short-lasting; 1: long-lasting), in which case one *run* consists of more than one *simulation* (P)
- ht_sample:** Probability density function used for the stochastic sampling of plume heights (0: uniform; 1: logarithmic)(P,V)
- ri_sample:** Probability density function used for the stochastic sampling of repose intervals (0: uniform; 1: logarithmic)(V)
- nb_runs:** Number of runs of the probabilistic eruption scenario(P,V)
- write_conf:** Write configuration files (Boolean 0/1). If this module is used to test ESP, choose **write_conf** = 0; if you plan on running the model afterwards, choose **write_conf** = 1(P,V)
- write_gs:** Write TGSD files (Boolean 0/1). If this module is used to test ESP, choose **write_gs** = 0; if you plan on running the model afterwards, choose **write_gs** = 1(P,V)
- write_fig_sep:** Save figures for separate eruptions of a given run. Useful when **long_lasting** = 1 or if running V-LLERS strategies(P,V)
- write_fig_all:** Save figures the entire run(P,V)
- write_log_sep:** Save a log file for separate eruptions of a given run(P,V)
- write_log_all:** Save a log file for the entire run(P,V)
- par:** Use the *Parallel Computing Toolbox* for *Matlab* if installed (Boolean 0/1)(P,V)
- par_cpu:** Number of CPU cores to use if **par** = 1(P,V)

⁸<http://www-das.uwo.edu/~geerts/cwx/notes/chap01/tropo.html>

Tephra2: Tephra2 parameters, refer to Bonadonna et al (2005) for more details

- eddy_const:** Eddy diffusion for small particles ($m^2 s^{-1}$) (P,V)
- diff_coeff:** Diffusion coefficient for large particles ($m^2 s^{-1}$) (P,V)
- ft_thresh:** Fall-time threshold for change in diffusion regimes (s) (P,V)
- lithic_dens:** Lithic density ($kg m^{-3}$) (P,V)
- pumice_dens:** Pumice density ($kg m^{-3}$) (P,V)
- col_step:** Column integration steps (P,V)
- part_step:** TGSD integration steps (P,V)
- alpha:** α parameter of the beta distribution used for mass distribution within the plume (P,V)
- alpha:** β parameter of the beta distribution used for mass distribution within the plume (P,V)

5.2 Structure of the output

Upon completion of either *ESP* function, a folder called after **run_name** is created in the *RUNS/* folder. It is possible to run several instances of the *ESP* functions with the same **run_name**, which will create sub-folders in the *RUNS/* folder. In that way, it is possible to explore how ESPs are distributed by the code without deleting previous runs. Each sub-folder contains two files:

- .mat:** The main project file. In the following step, when required to load a run, fetch this file.
- T2_stor.txt:** Ascii file containing all commands to be sent to Tephra2

In addition, eight folders are created and described here in chronological order rather than alphabetical:

- CONF/:** Contains the configuration files for Tephra2. The *CONF/* folder contains either a single folder named *all/* if **seasonality** = 0, or three folders named *all*, *dry* and *rainy* if **seasonality** = 1. Inside each folder are located as many sub-folders as **nb_runs**, which each contain either a single **.conf** file if **long_lasting** = 0 or several if **long_lasting** = 1. **.conf** files are ascii files.
- GS/:** Contains the TGSD (**.gsd**) ascii files sent to Tephra2, where the TGSD is expressed as the cumulative shape of a Gaussian distribution in ϕ units. In *TephraProb*, when **long_lasting** = 1, the same TGSD is used for the entire eruption.
- FIG/:** Contains the histograms summarizing the stochastic sampling of ESPs saved in vector **.eps** and *Matlab* **.fig** formats. The root folder contains histograms of ESPs over all runs. If **long_lasting** = 1, the **mass_sim** file represents the distribution of mass over all simulations (i.e. comprising all single simulation of a long-lasting run) whereas the **mass_run** file represents the sum of the mass of a given run. If **write_fig_sep** = 1, additional sub-folders are created containing distributions of ESPs for each separate run.
- LOG/:** Contains the log files for all runs. If **write_log_sep** = 1, log files for each separate run are also created.

The next four folders will only be populated when the eruption scenarios are ran with Tephra2 and will be further discussed in the post-processing section:

- OUT/:** Contains the Tephra2 output files, which are ascii **.conf** files arranged in 4 columns containing i) easting, ii) northing, iii) altitude and iv) ground accumulation ($kg m^{-2}$). Here again, each folder contains as many sub-folders as **nb_runs**, which each contain either a single **.out** file if **long_lasting** = 0 or several if **long_lasting** = 1.
- SUM/:** Contains the sum of all separate simulations of one run.

PROB/: Contains the probability matrices computed for a given threshold of tephra accumulation from a given scenario.

IM/: Contains the isomass matrices computed for a given probability of occurrence from a given scenario.

5.3 Running Tephra2

Upon the completion of the previous step, a file named **T2_stor.txt** was created. Each line of this file corresponds to a Tephra2 command with the following structure:

```
./path_to_model path_to_conf path_to_grid path_to_wind path_to_TGSD >> path_to_output
```

path_to_model: Path to Tephra2, typically MODEL/tephra2-2012 it *TephraProb*. In the command line, ./ is the command to an executable program;

path_to_conf: Path to the configuration file (.conf);

path_to_grid: Path to the grid file (.utm);

path_to_wind: Path to the wind file (.gen);

path_to_TGSD: Path to the total grain-size distribution file (.gsd);

path_to_output: Path to the output file (.out). In the command line, >> specifies the output file in which results will be saved.

5.3.1 Single-CPU machine

If you are running the probabilistic hazard assessment on your personal computer, do the following:

- From the main *TephraProb* interface, choose *Scenarios && Run TEPHRA2*
- When asked, select the .mat file of your project
- *Matlab* sends the command to the system

5.3.2 Computer cluster

There is no easy nor unique way to parallelize codes! So we can only assume that if you have access to a computer cluster, there will also be assistance. Conceptually, you need to:

- Upload the project file to the main node of your cluster. Remember that in *TephraProb*, **all paths are specified as relative**, meaning that you need to respect the hierarchy of directories. For instance, let's say i) your project is called **my_project** and ii) it is the second run in the project (e.g. 2/), you need to copy RUNS/my_project/2/ from your local to your remote machine.
- Move the **T2_stor.txt** file at the root level of your directory, i.e. along the MODEL, RUNS or WIND directories.
- Write a script that can read the content of **T2_stor.txt** and iterate through it, sending each command to a different CPU of each node.

Eventually, copy back the RUNS/my_project/2/OUT/ directory back to your local machine.

6 Post-processing

Post-processing functions included in *TephraProb* transform the results of individual eruption modelled using scenarios described above into probabilities of exceeding given thresholds of tephra accumulations. Following Bonadonna (2006), we want to quantify the probability the probability of hazardous thresholds of mass loads:

$$P[M(x, y) \geq M_T \mid \text{eruption}]$$

where $M(x, y)$ is the tephra mass load (kgm^{-2}) accumulated at given locations and M_T a mass load threshold. For a given eruption scenario, the probability P_M at coordinates x, y is quantified by counting the number of times a given threshold of load is reached over the total number of runs N_R :

$$P_M(x, y) = \frac{\sum_{i=1}^{N_R} n_i}{N_R}$$

where

$$n_i = \begin{cases} 1 & \text{if } M_i(x, y) \geq \text{threshold} \mid \text{eruption} \\ 0 & \text{otherwise.} \end{cases}$$

For the hazard assessment of tephra accumulation, we need to represent four variables including the geographic coordinates (x, y or longitude, latitude), the tephra accumulation and the probability of occurrence of a given tephra accumulation. However, typical displays such as a map are limited by three dimensions, and it is therefore necessary to fix a degree of freedom. *TephraProb* allows three main types of outputs presented below, which each fixes a different degree of freedom.

6.1 Probability maps

Probability maps fix a critical value of tephra accumulation ($kg m^{-2}$) to allow the contouring of the spatial probability of exceeding this critical threshold. To produce probability maps:

- From the main *TephraProb* interface, choose *Post processing > Probability calculations*
- When asked, select the `.mat` file of your project
- The first step consists in summing separate simulations of a given run
- The second step computes probabilities for a wide range of tephra accumulations at each pixel
- Per default, *TephraProb* computes probabilities of exceeding tephra accumulations of 0.01, 0.05, 0.5, 1, 5, 10, 25, 50, 75, 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, 600, 650, 700, 750, 800, 850, 900, 950 and 1000 $kg m^{-2}$. These values can be modified from the *File > Preferences* menu of the main interface. However, it is necessary to have a sufficiently large number of tephra accumulations when compiling probabilistic isomass maps
- Results are stored in the *PROB/* sub-folder of the *run.name* folder. Probability matrices are saved in three different formats:
 - *3C*: Column-type format (i.e. easting, northing, altitude and tephra accumulation), in which the number of rows of the file corresponds to the number of points in the grid. This format is useful for plotting with tools such as *GMT*⁹ or the Python module *Basemap*¹⁰
 - *GIS*: *ESRI ArcMap* ascii raster format, which can be imported into *ArcMap* using the *ascii to raster* conversion function¹¹
 - *MAT*: Matrix format, used for plotting within *TephraProb*

6.2 Hazard curves

Hazard curves fix the geographical location to allow the display of the probability of exceeding any tephra accumulation at a given point. To produce hazard curves:

- If the probability scenario was ran for a grid of points, create a list of points of interest using the *Input > Points* in the main *TephraProb* interface (see Section 4.1.2)
- From the main interface, choose *Post processing > Hazard curves*
- When asked, select the `.mat` file of your project

⁹<http://gmt.soest.hawaii.edu>

¹⁰<http://matplotlib.org/basemap/>

¹¹<http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#//00120000002s000000>

- When asked, select the `.points` file containing the points for which hazard curves will be computed. If the eruption scenario was ran to produce hazard curves only, this file should be in the same folder as `grid.pth`
- The code reads all files and saves the curves in the `CURVES/` folder of the root `TephraProb` folder

6.3 Probabilistic isomass maps

Probabilistic isomass maps fix a probability threshold to represent a typical tephra accumulation given a probability of occurrence of the hazardous phenomenon. The choice of the probability threshold, which can be regarded as an acceptable level of hazard, is a critical aspect that is the resort of decision makers. Scientists should therefore communicate results from probabilistic isomass maps with care. To produce probabilistic isomass maps:

- From the main `TephraProb` interface, choose *Post processing > Probabilistic isomass maps*
- When asked, select the `.mat` file of your project
- The code reads the probability matrices created in Section 6.1 for all thresholds of tephra accumulation and extracts the extent covered by a given probability of occurrence
- By default, `TephraProb` computes probabilistic isomass maps for probabilities of occurrence of 0.1, 0.25, 0.5, 0.75 and 0.9 (i.e. 10, 25, 50, 75 and 90 %). These values can be modified from the *File > Preferences* menu of the main interface
- Results are stored in the `PROB/` sub-folder of the `run_name` folder. Probabilistic isomass maps are saved in the same three formats as probability maps

7 Displaying and exporting results

The *Display* menu on the main `TephraProb` interface provides tools to visualize the outputs of the hazard assessment.

7.1 Distributions of ESP

The *Display figure* tools allows to display any *Matlab* figure with the extension `.fig` located in the `FIG/` sub-folder of the `run_name` folder. By default, these figures are set to be hidden, so opening them from your OS browser will not display them. Use this tool to display them and customize them the way you want.

7.2 Probability maps

The *Probability maps* tool allows to select and display probability maps. The maps are shown as filled contours and use the background obtained from *Google Maps*. To visualize them:

- From the main interface, choose *Display > Probability maps*
- When asked, select the `.mat` file of your project
- A window appears, which shows the probability matrices for all tephra accumulations. If the `seasonality` option was enabled, you will see three sets of matrices beginning with either *all*, *dry* or *rainy*. Typically, the files are named as `season_tephraThresh.prb`, where `tephraThresh` is an accumulation in $kg\ m^{-2}$
- Select a single or multiple entries and click OK
- Two aspects can be customized from the *File > Preferences* function of the main `TephraProb` interface:
 - The contour levels, which are set by default to 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9
 - The minimum probability to plot, which is set by default to 0.01 (i.e. 1%)

7.3 Probabilistic isomass maps

Displaying probabilistic isomass maps follows the same principle as the probability maps using the tool *Display > Probabilistic isomass maps*. In this case, two aspects can be customized from the *File > Preferences* function of the main *TephraProb* interface:

- The contour levels, which are set by default to 1, 10, 25, 50, 100, 300, 700 and 1000 $kg\ m^{-2}$
- The minimum tephra accumulation to plot, which is set by default to 0.01 $kg\ m^{-2}$

7.4 Hazard curves

Hazard curves for any **run_name** are located in the *CURVES/* folder of the main *TephraProb* folder. This allows to plot either i) results of different eruption scenarios for a given point or ii) the impact of a single eruption scenario on various points. To visualize hazard curves:

- From the main interface, choose *Display > Hazard curves*
- A window appears, which shows the computed hazard curves
- The curves are named as **name_run_season.out**, where **name** is the name of the point defined in 4.1.2, **run** is **run_name** and **season** is either *all*, *dry* or *rainy*.
- Select either one or multiple entries and click OK
- Hazard curves are shown as the probability of exceeding a given tephra accumulation (% , y-axis) as a function of the tephra accumulation ($kg\ m^{-2}$, x-axis)

Empirical parameters for Tephra2

The Tephra2 model relies on an analytical solution of the advection–diffusion equation, which accounts for two different regimes of sedimentation based on the terminal fall velocity of particles (Bonadonna et al, 2005)). Tephra2 requires the definition of the fall–time threshold acting as a threshold for the sedimentation of small particles (power–law diffusion) and large particles (linear diffusion), in which case a diffusion coefficient must be specified. These empirical parameters should typically be estimated by inverting field data with the method of Connor and Connor (2006), but Table 3 provides a list of empirical parameters for studied eruptions. The user is referred to the associated literature for more details on the selected eruptions.

	Fall-time threshold	Diffusion coefficient	References
	[s]	[$m^2 s^{-1}$]	
Cordon Caulle 2011	30500	3900	Elissondo et al (2016)
Vulcano Palizzi	255	1500	Biass et al (2016); Di Traglia (2011)
Fuego 1974	5000	4900	Biass et al (2016); Rose et al (2007)
Cotopaxi Layer 3	5911	3183	Biass and Bonadonna (2011, 2013)
Cotopaxi Layer 5	2044	1636	Biass and Bonadonna (2011, 2013)

Table 3: Empirical parameters for selected eruptions constrained by deposit inversion using Tephra2.

Description of the files

This section describes all the routines used in the *TephraProb* package

TephraProb/

tephraProb.m: Main interface of *TephraProb*

TephraProb/CODE/

- aggregate.m:** Aggregate the TGSD following the method of Bonadonna et al (2002b)
- check_project.m:** When loading a project, check if it was compiled with a previous version of *TephraProb*, in which case the user is prompted to update the necessary variables
- conf_grid.m:** Prepares calculations grids for *TephraProb* and Tephra2
- conf_points.m:** Set points of interest to use i) as a calculation grid or ii) as points to compute hazard curves
- display_figures.m:** Display *Matlab* .fig figure files
- get_prefs.m:** Preferences of the *TephraProb* package
- hazCurve_maker.m:** Computes hazard curves
- installECMWFAPI.m:** Install the ECMWF Python API libraries via Python
- load_project.m:** Load a *TephraProb* project
- load_run.m:** Load a *TephraProb* run
- plot_hazCurves.m:** Plot hazard curves
- plot_map_IM.m:** Plot probabilistic isomass maps
- plot_map_PROB.m:** Plot probability maps
- prob2IM.m:** Transforms probability matrices of exceeding a given tephra accumulation into a isomass maps for a given probability of occurrence
- probability_maker.m:** Retrieve output files of the Tephra2 model and computes them into probability matrices
- runProb_vulc.m:** Creates ESPs for various probabilistic Vulcanian eruption scenarios

runProb.m: Creates ESPs for various probabilistic sub-Plinian/Plinian eruption scenarios
runT2.m: Runs the Tephra2 model
writeDEM.m: Write data into an *ESRI ArcMap* ascii raster
writelt.m: Write data into an ascii file

TephraProb/CODE/dwind/

analyze_wind.m: Main GUI to analyze and plot wind conditions
dwind_ECMWF.m: Download NetCDF wind files from the ECMWF ERA-Interim dataset
dwind_NOAA.m: Download NetCDF wind files from the NOAA NCEP/NCAR dataset
installECMWFAPI.m: Uses the system function to install the ECMWF Python Api libraries
prctile.m: Returns the given percentile of a population
process_wind.m: Convert NetCDF files into ascii wind profiles
analyze_wind.m: Writes the .ecmwfapirc file to user folder

TephraProb/CODE/gvp/

gvp.m: Access the GVP database, retrieves the data and provides a GUI to plot the results and calculate probabilities of eruptions

TephraProb/CODE/dependencies/ These files are contributions to the *Matlab File Exchange* platform¹², and all credit goes to their respective authors!

contourcs.m: By Kesh Ikuma, contribution 28447
errorbar_x.m: By Goetz Huesken, contribution 12751
freezeColors.m: By John Iversen, contribution 7943
get_mer.m: By Wim Degruyter, *Gephysical Research Letters*, 39, 16
htmlTableToCell.m: By Steinar Elgsaeter, contribution 34968
linspecer.m: By Jonathan C. Lansey, contribution 42673
ll2utm.m: By Francois Beauducel, contribution 45699
plot_google_map.m: By Zohar Bar-Yehuda, contribution 27627
utm2ll.m: By Francois Beauducel, contribution 45699
WindRose.m: By Daniel Pereira, contribution 47248

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¹²<http://www.mathworks.com/matlabcentral/fileexchange/>

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