TephraProb

Sebastien Biass[1,2]
Costanza Bonadonna[1]
Laura Connor[3]
Chuck Connor[3]

1. *Section of Earth and Environmental Sciences, University of Geneva, 13, rue des Maraichers, 1205 Geneva, Switzerland*
2. *Department of Geology and Geophysics, University of Hawai'i at Manoa, 1680 East–West Road, HI 96822 Honolulu, USA*
3. *University of South Florida, 4202 E. Fowler Ave, FL 33620 Tampa, USA*

User manual

April 2016 (Last updated February 2017)

Contents

List of Figures

List of Tables

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 *TephraProb* 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	Set ECMWF API Key	Writes the ECMWF API Key received from registration
		Install ECMWF libraries	Install the necessary Python libraries
		Download NOAA wind	Download wind data from the NOAA NCEP/NCAR Reanalysis dataset (Kalnay et al, 1996)
		Download ECMWF wind	Download wind data from the ECMWF Era–Interim dataset (Dee et al, 2011)
		Process wind	Convert NetCDF files to ascii wind profiles
		Analyze wind	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	**Display figure**		Display any type of figure created during the generation of ESPs (e.g. histograms of each separate ESP)
	Probability maps		Display probability maps using a background from *Google Maps*
	Probabilistic isomass maps		Display probabilistic isomass maps using a background from *Google Maps*
	Hazard curves		Display hazard curves

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

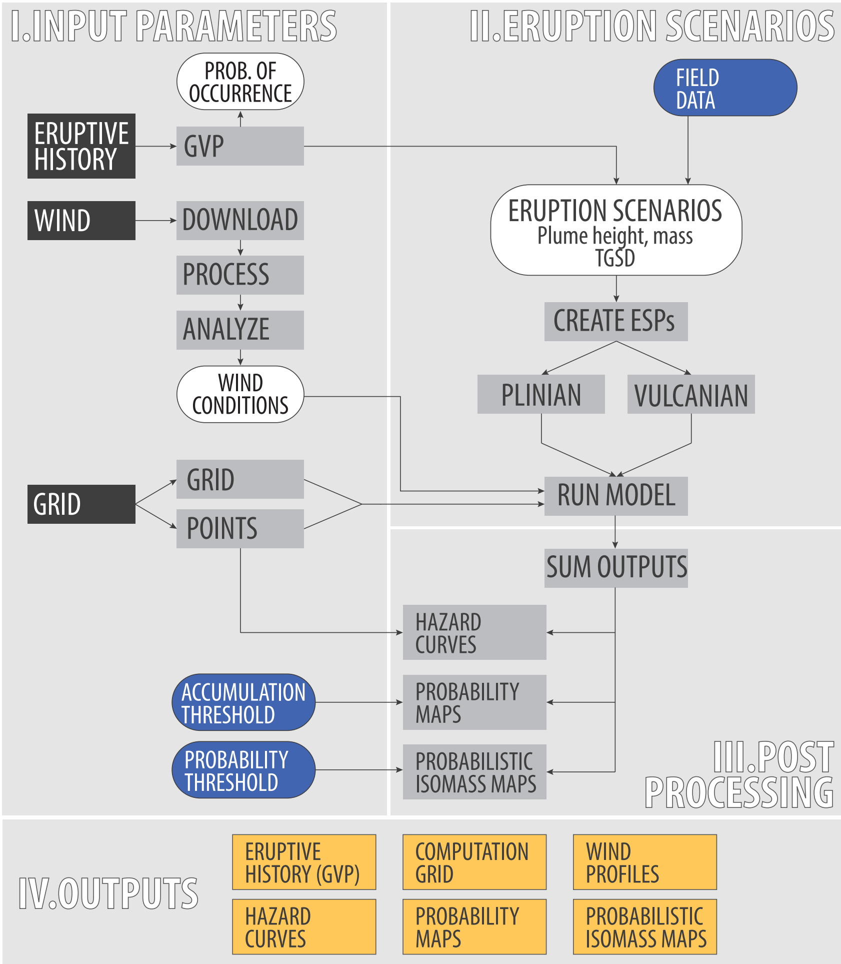

Figure 1: Workflow implemented in *TephraProb*, including 3 main sections to i) access and pre–process the necessary input data, ii) run a large range of probabilistic eruption scenarios and iii) post–process the model outputs into a comprehensive set of probabilistic tools.

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 latitude [2]. 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

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

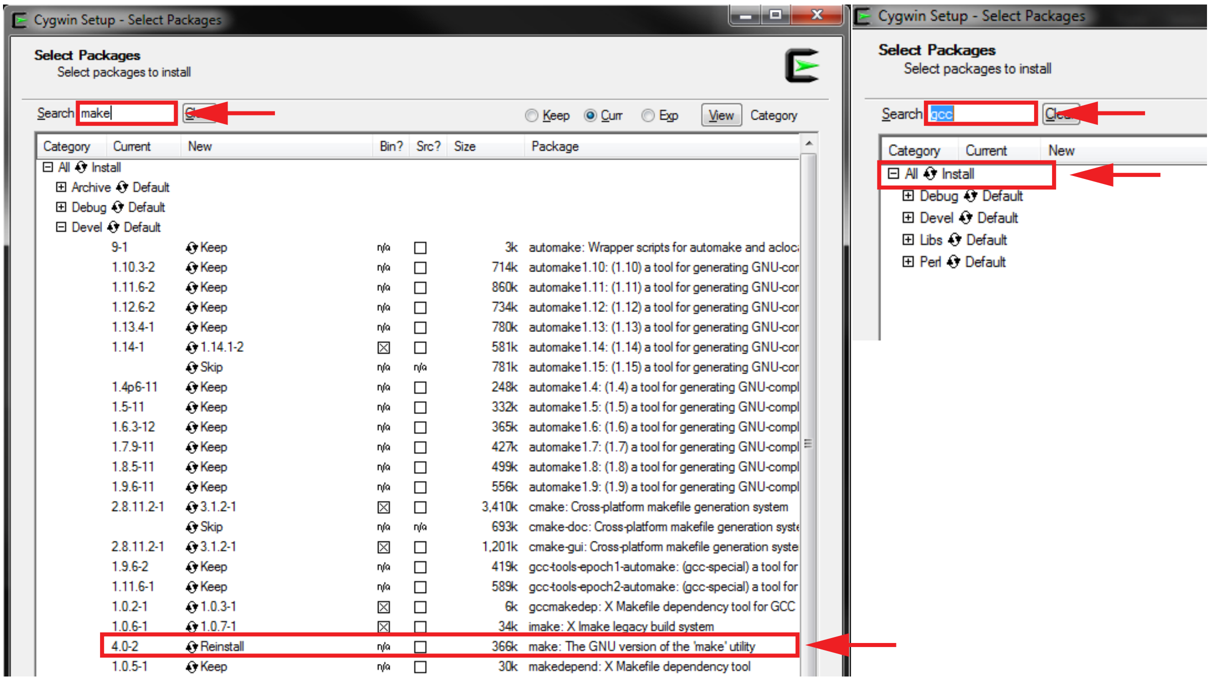

Figure 2: Additional packages required during the *Cygwin* install. Make sure to install the *Make* utility (left) and the *GCC* compiler (right).

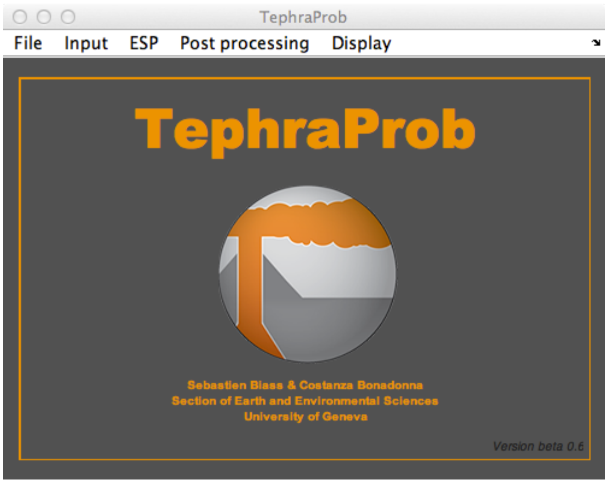

Figure 3: Main interface of the *TephraProb* package.

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

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

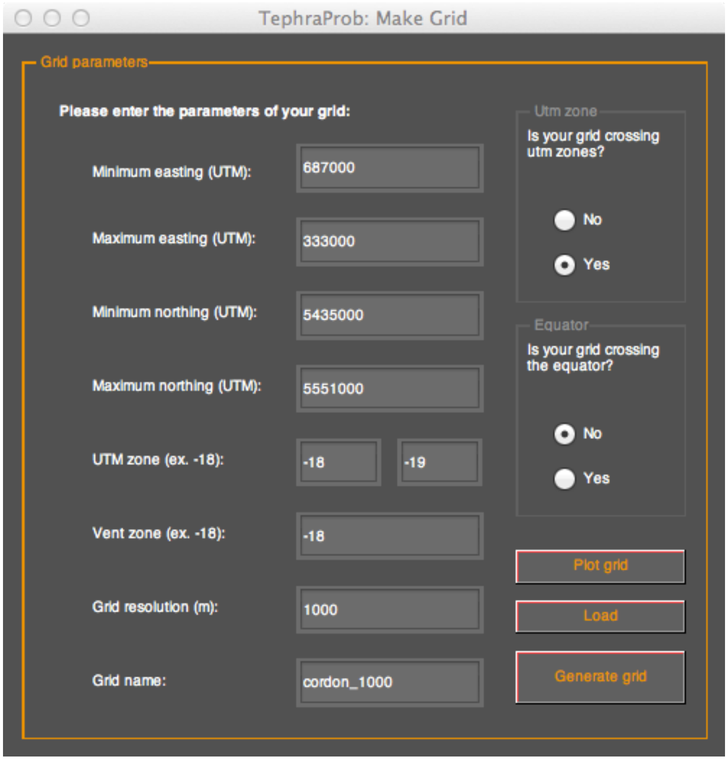

Figure 4: Interface for generating calculation grids.

- _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

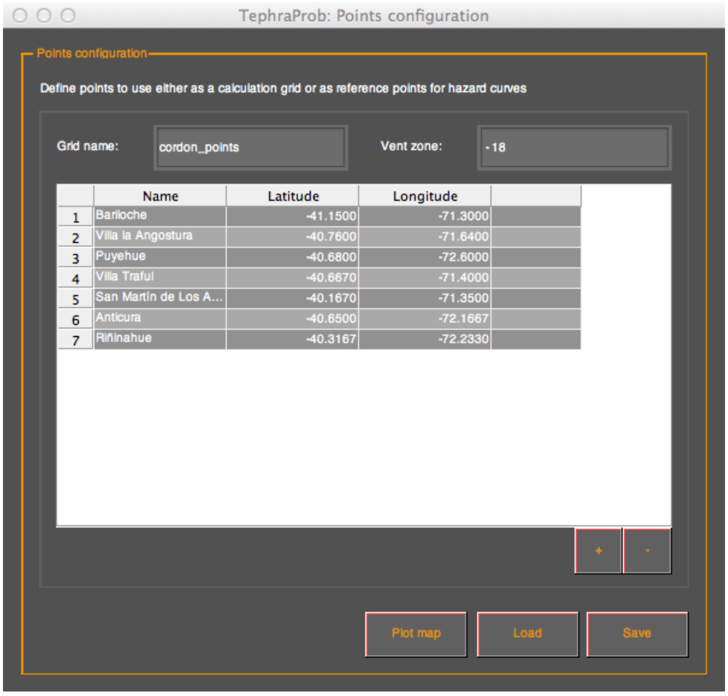

Figure 5: Interface for generating points of interest.

NCEP/NCAR Reanalysis 1 dataset contains data since 1948/01/01[3] and the NCEP-DOE Reanalysis 2 since 1979/01/01[4]. 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 levels [5].

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 fille 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`

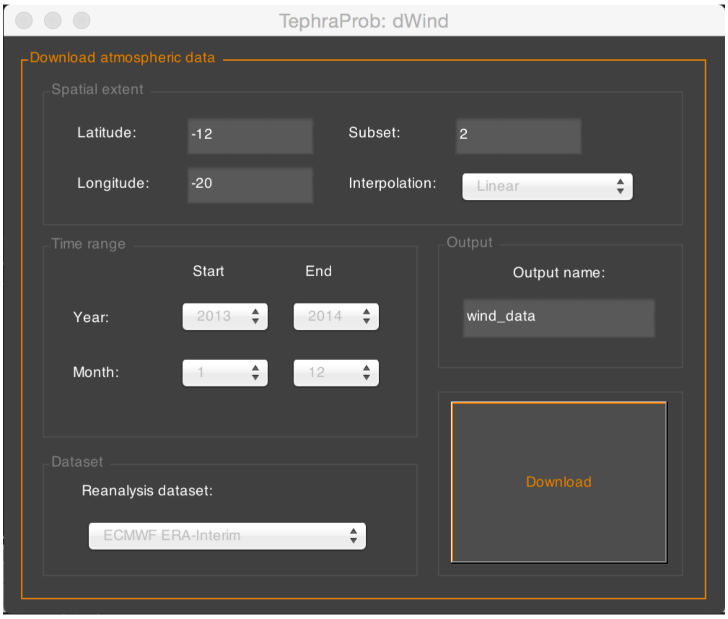

Figure 6: Interface to download wind data.

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* wind 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 ± interquartile range (i.e. 25^{th} and 75^{th} percentiles of the population) or as the mean ± 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`

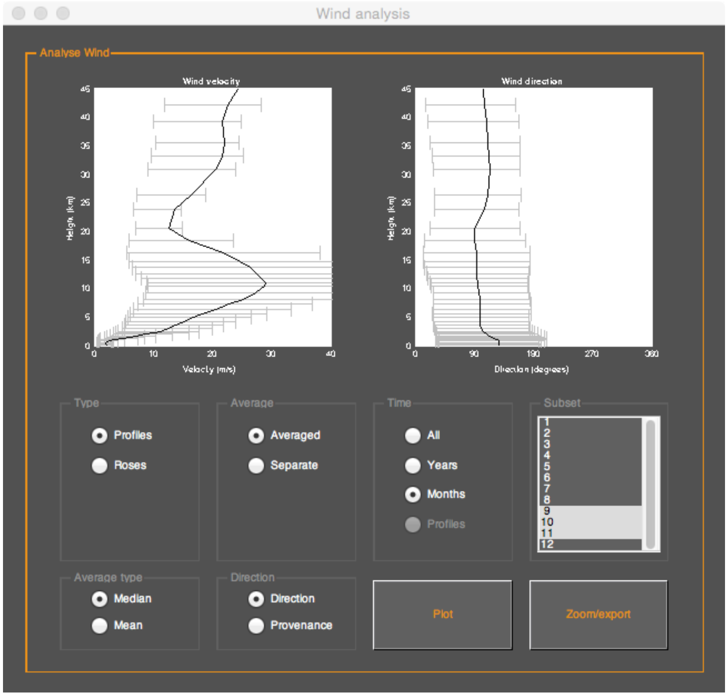

Figure 7: Interface to analyze wind conditions

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 Institute[7] (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 identifyl 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`

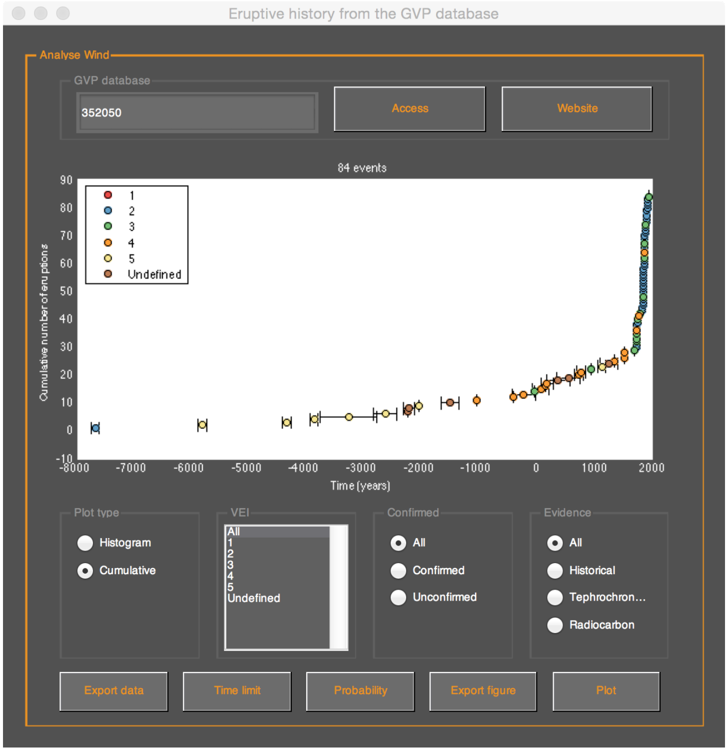

Figure 8: Interface to analyze the eruptive history from the GVP database.

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. Cick 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

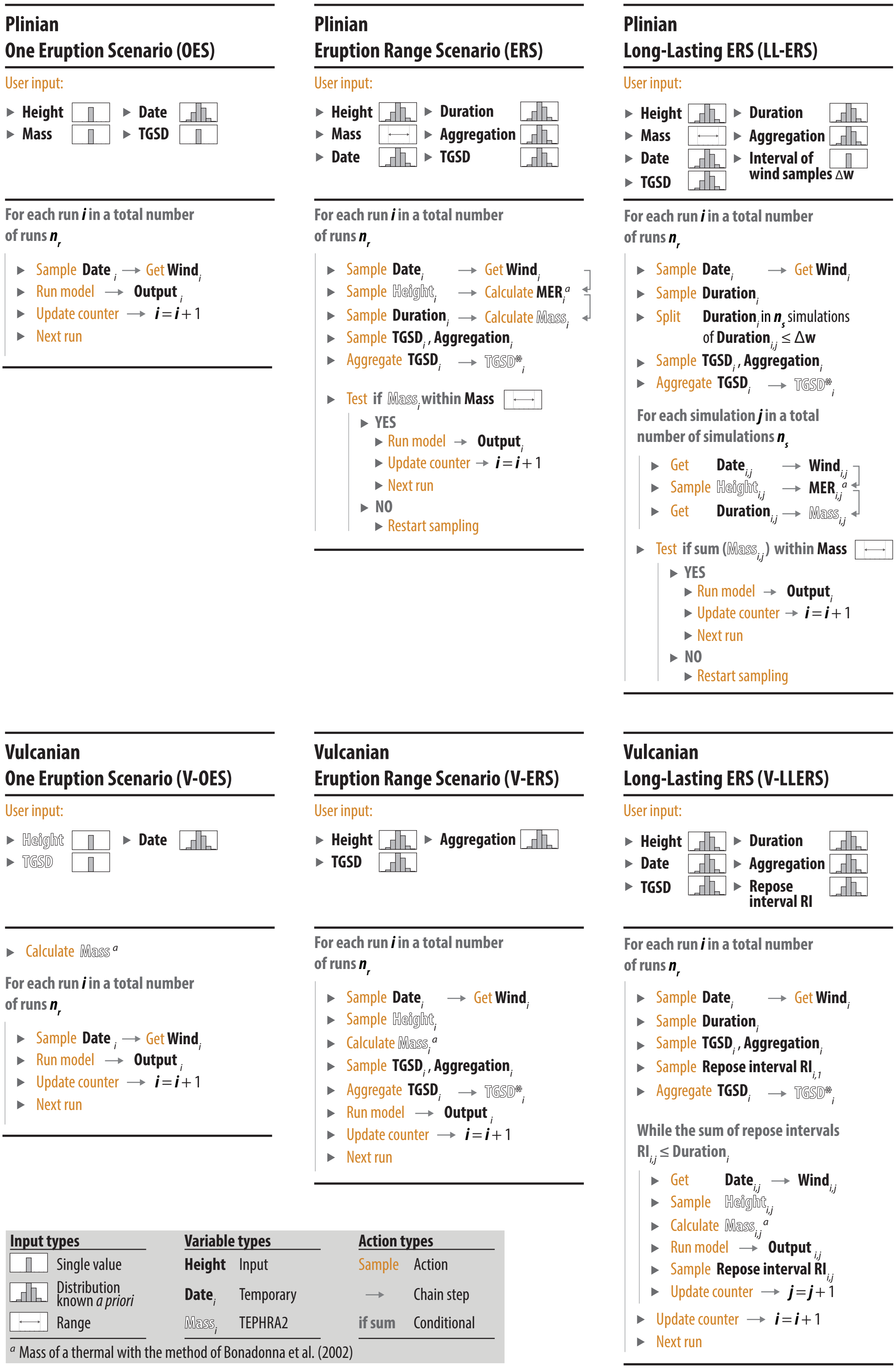

Figure 9: Algorithms used to generate ESPs for the main eruption scenarios implemented in *TephraProb*. The top three algorithms refer to sub–Plinian/Plinian types of eruptions. The bottom three algorithms are designed for Vulcanian type of eruptions.

- 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.uwyo.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:

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

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 function [11]
  - *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

writeIt.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, retreives 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* platform[12], 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

References

Biass S, Bonadonna C (2011) A quantitative uncertainty assessment of eruptive parameters derived from tephra deposits: the example of two large eruptions of Cotopaxi volcano, Ecuador. Bulletin of Volcanology 73(1):73–90

Biass S, Bonadonna C (2013) A fast GIS-based risk assessment for tephra fallout: the example of Cotopaxi volcano, Ecuador-Part I: probabilistic hazard assessment. Natural Hazards 65(1):477–495

Biass S, Scaini C, Bonadonna C, Folch A, Smith K, Höskuldsson A (2014) A multi-scale risk assessment for tephra fallout and airborne concentration from multiple Icelandic volcanoes - Part 1: Hazard assessment. Nat Hazards Earth Syst Sci 14(8):2265–2287, DOI 10.5194/nhess-14-2265-2014

Biass S, Bonadonna C, Traglia F, Pistolesi M, Rosi M, Lestuzzi P (2016) Probabilistic evaluation of the physical impact of future tephra fallout events for the Island of Vulcano, Italy. Bulletin of Volcanology 78(5):1–22, DOI 10.1007/s00445-016-1028-1, URL `http://dx.doi.org/10.1007/s00445-016-1028-1`

[12] `http://www.mathworks.com/matlabcentral/fileexchange/`

Bonadonna C (2006) Probabilistic modelling of tephra dispersion. Statistics in Volcanology pp 243–259

Bonadonna C, Houghton B (2005) Total grain-size distribution and volume of tephra-fall deposits. Bull Volcanol 67(5):441–456

Bonadonna C, Macedonio G, Sparks R (2002a) Numerical modelling of tephra fallout associated with dome collapses and Vulcanian explosions: application to hazard assessment on Montserrat. In: Druitt T, Kokelaar B (eds) The eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999, vol 21, Geological Society, London, pp 483–516

Bonadonna C, Mayberry G, Calder E, Sparks R, Choux C, Jackson P, Lejeune A, Loughlin S, Norton G, Rose WI, Ryan G, Young S (2002b) Tephra fallout in the eruption of Soufrière Hills Volcano, Montserrat. In: Druitt T, Kokelaar B (eds) The eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999, vol 21, Geological Society, London, pp 483–516

Bonadonna C, Connor CB, Houghton BF, Connor L, Byrne M, Laing A, Hincks TK (2005) Probabilistic modeling of tephra dispersal: Hazard assessment of a multiphase rhyolitic eruption at Tarawera, New Zealand. J Geophys Res 110(10.1029)

Borradaile GJ (2003) Statistics of earth science data: their distribution in time, space, and orientation. Springer Verlag, Berlin

Connor LJ, Connor CB (2006) Inversion is the key to dispersion: understanding eruption dynamics by inverting tephra fallout. In: Mader HM, Coles SG, Connor CB, Connor LJ (eds) Statistics in volcanology, Geological Society of London, London, pp 231–242

Dee DP, Uppala SM, Simmons AJ, Berrisford P, Poli P, Kobayashi S, Andrae U, Balmaseda MA, Balsamo G, Bauer P, Bechtold P, Beljaars ACM, van de Berg L, Bidlot J, Bormann N, Delsol C, Dragani R, Fuentes M, Geer AJ, Haimberger L, Healy SB, Hersbach H, Hólm EV, Isaksen L, Kållberg P, Köhler M, Matricardi M, McNally AP, Monge-Sanz BM, Morcrette JJ, Park BK, Peubey C, de Rosnay P, Tavolato C, Thépaut JN, Vitart F (2011) The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Quarterly Journal of the Royal Meteorological Society 137(656):553–597, DOI 10.1002/qj.828

Degruyter W, Bonadonna C (2012) Improving on mass flow rate estimates of volcanic eruptions. Geophys Res Lett 39(16), DOI 10.1029/2012GL052566

Di Traglia F (2011) The last 1000 years of eruptive activity at the Fossa Cone (Island of Vulcano, Southern Italy). PhD thesis, Università di Pisa

Dzierma Y, Wehrmann H (2010) Eruption time series statistically examined: Probabilities of future eruptions at Villarrica and Llaima Volcanoes, Southern Volcanic Zone, Chile. Journal of Volcanology and Geothermal Research 193(1-2):82–92

Elissondo M, Baumann V, Bonadonna C, Pistolesi M, Cioni R, Bertagnini A, Biass S, Herrero JC, Gonzalez R (2016) Chronology and impact of the 2011 Cordón Caulle eruption, Chile. Nat Hazards Earth Syst Sci 16(3):675–704, DOI 10.5194/nhess-16-675-2016

Hurst T, Smith W (2004) A Monte Carlo methodology for modelling ashfall hazards. Journal of volcanology and geothermal research 138(3-4):393–403

Kalnay EC, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J (1996) The NCEP/NCAR 40-year reanalysis project. Bulletin of the American Meteorological Society 77(3):437–471

Kanamitsu M, Ebisuzaki W, Woollen J, Yang SK, Hnilo JJ, Fiorino M, Potter GL (2002) NCEP-DOE AMIP-II reanalysis (R-2). Bulletin of the American Meteorological Society 83(11):1631–1643+1559, DOI 10.1175/BAMS-83-11-1631

Rose WI, Self S, Murrow PJ, Bonadonna C, Durant AJ, Ernst GGJ (2007) Nature and significance of small volume fall deposits at composite volcanoes: Insights from the October 14, 1974 Fuego eruption, Guatemala. Bulletin of Volcanology 70(9):1043–1067, DOI 10.1007/s00445-007-0187-5, URL `http://dx.doi.org/10.1007/s00445-007-0187-5`

Siebert L, Simkin T, Kimberly P (2010) Volcanoes of the World. University of California Press, Berkley

Simkin T, Siebert L (1994) Volcanoes of the World. Geoscience Press, Tucson, AZ

License

Preamble

The GNU General Public License is a free, copyleft license for software and other kinds of works.

The licenses for most software and other practical works are designed to take away your freedom to share and change the works. By contrast, the GNU General Public License is intended to guarantee your freedom to share and change all versions of a program–to make sure it remains free software for all its users. We, the Free Software Foundation, use the GNU General Public License for most of our software; it applies also to any other work released this way by its authors. You can apply it to your programs, too.

When we speak of free software, we are referring to freedom, not price. Our General Public Licenses are designed to make sure that you have the freedom to distribute copies of free software (and charge for them if you wish), that you receive source code or can get it if you want it, that you can change the software or use pieces of it in new free programs, and that you know you can do these things.

To protect your rights, we need to prevent others from denying you these rights or asking you to surrender the rights. Therefore, you have certain responsibilities if you distribute copies of the software, or if you modify it: responsibilities to respect the freedom of others.

For example, if you distribute copies of such a program, whether gratis or for a fee, you must pass on to the recipients the same freedoms that you received. You must make sure that they, too, receive or can get the source code. And you must show them these terms so they know their rights.

Developers that use the GNU GPL protect your rights with two steps: (1) assert copyright on the software, and (2) offer you this License giving you legal permission to copy, distribute and/or modify it.

For the developers' and authors' protection, the GPL clearly explains that there is no warranty for this free software. For both users' and authors' sake, the GPL requires that modified versions be marked as changed, so that their problems will not be attributed erroneously to authors of previous versions.

Some devices are designed to deny users access to install or run modified versions of the software inside them, although the manufacturer can do so. This is fundamentally incompatible with the aim of protecting users' freedom to change the software. The systematic pattern of such abuse occurs in the area of products for individuals to use, which is precisely where it is most unacceptable. Therefore, we have designed this version of the GPL to prohibit the practice for those products. If such problems arise substantially in other domains, we stand ready to extend this provision to those domains in future versions of the GPL, as needed to protect the freedom of users.

Finally, every program is threatened constantly by software patents. States should not allow patents to restrict development and use of software on general-purpose computers, but in those that do, we wish to avoid the special danger that patents applied to a free program could make it effectively proprietary. To prevent this, the GPL assures that patents cannot be used to render the program non-free.

The precise terms and conditions for copying, distribution and modification follow.

Terms and Conditions

0. Definitions.

   "This License" refers to version 3 of the GNU General Public License.

   "Copyright" also means copyright-like laws that apply to other kinds of works, such as semiconductor masks.

   "The Program" refers to any copyrightable work licensed under this License. Each licensee is addressed as "you". "Licensees" and "recipients" may be individuals or organizations.

   To "modify" a work means to copy from or adapt all or part of the work in a fashion requiring copyright permission, other than the making of an exact copy. The resulting work is called a "modified version" of the earlier work or a work "based on" the earlier work.

   A "covered work" means either the unmodified Program or a work based on the Program.

To “propagate” a work means to do anything with it that, without permission, would make you directly or secondarily liable for infringement under applicable copyright law, except executing it on a computer or modifying a private copy. Propagation includes copying, distribution (with or without modification), making available to the public, and in some countries other activities as well.

To “convey” a work means any kind of propagation that enables other parties to make or receive copies. Mere interaction with a user through a computer network, with no transfer of a copy, is not conveying.

An interactive user interface displays “Appropriate Legal Notices” to the extent that it includes a convenient and prominently visible feature that (1) displays an appropriate copyright notice, and (2) tells the user that there is no warranty for the work (except to the extent that warranties are provided), that licensees may convey the work under this License, and how to view a copy of this License. If the interface presents a list of user commands or options, such as a menu, a prominent item in the list meets this criterion.

1. Source Code.

   The “source code” for a work means the preferred form of the work for making modifications to it. “Object code” means any non-source form of a work.

   A “Standard Interface” means an interface that either is an official standard defined by a recognized standards body, or, in the case of interfaces specified for a particular programming language, one that is widely used among developers working in that language.

   The “System Libraries” of an executable work include anything, other than the work as a whole, that (a) is included in the normal form of packaging a Major Component, but which is not part of that Major Component, and (b) serves only to enable use of the work with that Major Component, or to implement a Standard Interface for which an implementation is available to the public in source code form. A “Major Component”, in this context, means a major essential component (kernel, window system, and so on) of the specific operating system (if any) on which the executable work runs, or a compiler used to produce the work, or an object code interpreter used to run it.

   The “Corresponding Source” for a work in object code form means all the source code needed to generate, install, and (for an executable work) run the object code and to modify the work, including scripts to control those activities. However, it does not include the work’s System Libraries, or general-purpose tools or generally available free programs which are used unmodified in performing those activities but which are not part of the work. For example, Corresponding Source includes interface definition files associated with source files for the work, and the source code for shared libraries and dynamically linked subprograms that the work is specifically designed to require, such as by intimate data communication or control flow between those subprograms and other parts of the work.

   The Corresponding Source need not include anything that users can regenerate automatically from other parts of the Corresponding Source.

   The Corresponding Source for a work in source code form is that same work.

2. Basic Permissions.

   All rights granted under this License are granted for the term of copyright on the Program, and are irrevocable provided the stated conditions are met. This License explicitly affirms your unlimited permission to run the unmodified Program. The output from running a covered work is covered by this License only if the output, given its content, constitutes a covered work. This License acknowledges your rights of fair use or other equivalent, as provided by copyright law.

   You may make, run and propagate covered works that you do not convey, without conditions so long as your license otherwise remains in force. You may convey covered works to others for the sole purpose of having them make modifications exclusively for you, or provide you with facilities for running those works, provided that you comply with the terms of this License in conveying all material for which you do not control copyright. Those thus making or running the covered works for you must do so exclusively on your behalf, under your direction and control, on terms that prohibit them from making any copies of your copyrighted material outside their relationship with you.

Conveying under any other circumstances is permitted solely under the conditions stated below. Sublicensing is not allowed; section 10 makes it unnecessary.

3. Protecting Users' Legal Rights From Anti-Circumvention Law.

   No covered work shall be deemed part of an effective technological measure under any applicable law fulfilling obligations under article 11 of the WIPO copyright treaty adopted on 20 December 1996, or similar laws prohibiting or restricting circumvention of such measures.

   When you convey a covered work, you waive any legal power to forbid circumvention of technological measures to the extent such circumvention is effected by exercising rights under this License with respect to the covered work, and you disclaim any intention to limit operation or modification of the work as a means of enforcing, against the work's users, your or third parties' legal rights to forbid circumvention of technological measures.

4. Conveying Verbatim Copies.

   You may convey verbatim copies of the Program's source code as you receive it, in any medium, provided that you conspicuously and appropriately publish on each copy an appropriate copyright notice; keep intact all notices stating that this License and any non-permissive terms added in accord with section 7 apply to the code; keep intact all notices of the absence of any warranty; and give all recipients a copy of this License along with the Program.

   You may charge any price or no price for each copy that you convey, and you may offer support or warranty protection for a fee.

5. Conveying Modified Source Versions.

   You may convey a work based on the Program, or the modifications to produce it from the Program, in the form of source code under the terms of section 4, provided that you also meet all of these conditions:

   (a) The work must carry prominent notices stating that you modified it, and giving a relevant date.
   (b) The work must carry prominent notices stating that it is released under this License and any conditions added under section 7. This requirement modifies the requirement in section 4 to "keep intact all notices".
   (c) You must license the entire work, as a whole, under this License to anyone who comes into possession of a copy. This License will therefore apply, along with any applicable section 7 additional terms, to the whole of the work, and all its parts, regardless of how they are packaged. This License gives no permission to license the work in any other way, but it does not invalidate such permission if you have separately received it.
   (d) If the work has interactive user interfaces, each must display Appropriate Legal Notices; however, if the Program has interactive interfaces that do not display Appropriate Legal Notices, your work need not make them do so.

   A compilation of a covered work with other separate and independent works, which are not by their nature extensions of the covered work, and which are not combined with it such as to form a larger program, in or on a volume of a storage or distribution medium, is called an "aggregate" if the compilation and its resulting copyright are not used to limit the access or legal rights of the compilation's users beyond what the individual works permit. Inclusion of a covered work in an aggregate does not cause this License to apply to the other parts of the aggregate.

6. Conveying Non-Source Forms.

   You may convey a covered work in object code form under the terms of sections 4 and 5, provided that you also convey the machine-readable Corresponding Source under the terms of this License, in one of these ways:

   (a) Convey the object code in, or embodied in, a physical product (including a physical distribution medium), accompanied by the Corresponding Source fixed on a durable physical medium customarily used for software interchange.

(b) Convey the object code in, or embodied in, a physical product (including a physical distribution medium), accompanied by a written offer, valid for at least three years and valid for as long as you offer spare parts or customer support for that product model, to give anyone who possesses the object code either (1) a copy of the Corresponding Source for all the software in the product that is covered by this License, on a durable physical medium customarily used for software interchange, for a price no more than your reasonable cost of physically performing this conveying of source, or (2) access to copy the Corresponding Source from a network server at no charge.

(c) Convey individual copies of the object code with a copy of the written offer to provide the Corresponding Source. This alternative is allowed only occasionally and noncommercially, and only if you received the object code with such an offer, in accord with subsection 6b.

(d) Convey the object code by offering access from a designated place (gratis or for a charge), and offer equivalent access to the Corresponding Source in the same way through the same place at no further charge. You need not require recipients to copy the Corresponding Source along with the object code. If the place to copy the object code is a network server, the Corresponding Source may be on a different server (operated by you or a third party) that supports equivalent copying facilities, provided you maintain clear directions next to the object code saying where to find the Corresponding Source. Regardless of what server hosts the Corresponding Source, you remain obligated to ensure that it is available for as long as needed to satisfy these requirements.

(e) Convey the object code using peer-to-peer transmission, provided you inform other peers where the object code and Corresponding Source of the work are being offered to the general public at no charge under subsection 6d.

A separable portion of the object code, whose source code is excluded from the Corresponding Source as a System Library, need not be included in conveying the object code work.

A "User Product" is either (1) a "consumer product", which means any tangible personal property which is normally used for personal, family, or household purposes, or (2) anything designed or sold for incorporation into a dwelling. In determining whether a product is a consumer product, doubtful cases shall be resolved in favor of coverage. For a particular product received by a particular user, "normally used" refers to a typical or common use of that class of product, regardless of the status of the particular user or of the way in which the particular user actually uses, or expects or is expected to use, the product. A product is a consumer product regardless of whether the product has substantial commercial, industrial or non-consumer uses, unless such uses represent the only significant mode of use of the product.

"Installation Information" for a User Product means any methods, procedures, authorization keys, or other information required to install and execute modified versions of a covered work in that User Product from a modified version of its Corresponding Source. The information must suffice to ensure that the continued functioning of the modified object code is in no case prevented or interfered with solely because modification has been made.

If you convey an object code work under this section in, or with, or specifically for use in, a User Product, and the conveying occurs as part of a transaction in which the right of possession and use of the User Product is transferred to the recipient in perpetuity or for a fixed term (regardless of how the transaction is characterized), the Corresponding Source conveyed under this section must be accompanied by the Installation Information. But this requirement does not apply if neither you nor any third party retains the ability to install modified object code on the User Product (for example, the work has been installed in ROM).

The requirement to provide Installation Information does not include a requirement to continue to provide support service, warranty, or updates for a work that has been modified or installed by the recipient, or for the User Product in which it has been modified or installed. Access to a network may be denied when the modification itself materially and adversely affects the operation of the network or violates the rules and protocols for communication across the network.

Corresponding Source conveyed, and Installation Information provided, in accord with this section must be in a format that is publicly documented (and with an implementation available to the public in source code form), and must require no special password or key for unpacking, reading or copying.

7. Additional Terms.

   "Additional permissions" are terms that supplement the terms of this License by making exceptions from one or more of its conditions. Additional permissions that are applicable to the entire Program shall be treated as though they were included in this License, to the extent that they are valid under applicable law. If additional permissions apply only to part of the Program, that part may be used separately under those permissions, but the entire Program remains governed by this License without regard to the additional permissions.

   When you convey a copy of a covered work, you may at your option remove any additional permissions from that copy, or from any part of it. (Additional permissions may be written to require their own removal in certain cases when you modify the work.) You may place additional permissions on material, added by you to a covered work, for which you have or can give appropriate copyright permission.

   Notwithstanding any other provision of this License, for material you add to a covered work, you may (if authorized by the copyright holders of that material) supplement the terms of this License with terms:

   (a) Disclaiming warranty or limiting liability differently from the terms of sections 15 and 16 of this License; or
   (b) Requiring preservation of specified reasonable legal notices or author attributions in that material or in the Appropriate Legal Notices displayed by works containing it; or
   (c) Prohibiting misrepresentation of the origin of that material, or requiring that modified versions of such material be marked in reasonable ways as different from the original version; or
   (d) Limiting the use for publicity purposes of names of licensors or authors of the material; or
   (e) Declining to grant rights under trademark law for use of some trade names, trademarks, or service marks; or
   (f) Requiring indemnification of licensors and authors of that material by anyone who conveys the material (or modified versions of it) with contractual assumptions of liability to the recipient, for any liability that these contractual assumptions directly impose on those licensors and authors.

   All other non-permissive additional terms are considered "further restrictions" within the meaning of section 10. If the Program as you received it, or any part of it, contains a notice stating that it is governed by this License along with a term that is a further restriction, you may remove that term. If a license document contains a further restriction but permits relicensing or conveying under this License, you may add to a covered work material governed by the terms of that license document, provided that the further restriction does not survive such relicensing or conveying.

   If you add terms to a covered work in accord with this section, you must place, in the relevant source files, a statement of the additional terms that apply to those files, or a notice indicating where to find the applicable terms.

   Additional terms, permissive or non-permissive, may be stated in the form of a separately written license, or stated as exceptions; the above requirements apply either way.

8. Termination.

   You may not propagate or modify a covered work except as expressly provided under this License. Any attempt otherwise to propagate or modify it is void, and will automatically terminate your rights under this License (including any patent licenses granted under the third paragraph of section 11).

   However, if you cease all violation of this License, then your license from a particular copyright holder is reinstated (a) provisionally, unless and until the copyright holder explicitly and finally terminates your license, and (b) permanently, if the copyright holder fails to notify you of the violation by some reasonable means prior to 60 days after the cessation.

   Moreover, your license from a particular copyright holder is reinstated permanently if the copyright holder notifies you of the violation by some reasonable means, this is the first time you have received notice of violation of this License (for any work) from that copyright holder, and you cure the violation prior to 30 days after your receipt of the notice.

Termination of your rights under this section does not terminate the licenses of parties who have received copies or rights from you under this License. If your rights have been terminated and not permanently reinstated, you do not qualify to receive new licenses for the same material under section 10.

9. Acceptance Not Required for Having Copies.

   You are not required to accept this License in order to receive or run a copy of the Program. Ancillary propagation of a covered work occurring solely as a consequence of using peer-to-peer transmission to receive a copy likewise does not require acceptance. However, nothing other than this License grants you permission to propagate or modify any covered work. These actions infringe copyright if you do not accept this License. Therefore, by modifying or propagating a covered work, you indicate your acceptance of this License to do so.

10. Automatic Licensing of Downstream Recipients.

    Each time you convey a covered work, the recipient automatically receives a license from the original licensors, to run, modify and propagate that work, subject to this License. You are not responsible for enforcing compliance by third parties with this License.

    An "entity transaction" is a transaction transferring control of an organization, or substantially all assets of one, or subdividing an organization, or merging organizations. If propagation of a covered work results from an entity transaction, each party to that transaction who receives a copy of the work also receives whatever licenses to the work the party's predecessor in interest had or could give under the previous paragraph, plus a right to possession of the Corresponding Source of the work from the predecessor in interest, if the predecessor has it or can get it with reasonable efforts.

    You may not impose any further restrictions on the exercise of the rights granted or affirmed under this License. For example, you may not impose a license fee, royalty, or other charge for exercise of rights granted under this License, and you may not initiate litigation (including a cross-claim or counterclaim in a lawsuit) alleging that any patent claim is infringed by making, using, selling, offering for sale, or importing the Program or any portion of it.

11. Patents.

    A "contributor" is a copyright holder who authorizes use under this License of the Program or a work on which the Program is based. The work thus licensed is called the contributor's "contributor version".

    A contributor's "essential patent claims" are all patent claims owned or controlled by the contributor, whether already acquired or hereafter acquired, that would be infringed by some manner, permitted by this License, of making, using, or selling its contributor version, but do not include claims that would be infringed only as a consequence of further modification of the contributor version. For purposes of this definition, "control" includes the right to grant patent sublicenses in a manner consistent with the requirements of this License.

    Each contributor grants you a non-exclusive, worldwide, royalty-free patent license under the contributor's essential patent claims, to make, use, sell, offer for sale, import and otherwise run, modify and propagate the contents of its contributor version.

    In the following three paragraphs, a "patent license" is any express agreement or commitment, however denominated, not to enforce a patent (such as an express permission to practice a patent or covenant not to sue for patent infringement). To "grant" such a patent license to a party means to make such an agreement or commitment not to enforce a patent against the party.

    If you convey a covered work, knowingly relying on a patent license, and the Corresponding Source of the work is not available for anyone to copy, free of charge and under the terms of this License, through a publicly available network server or other readily accessible means, then you must either (1) cause the Corresponding Source to be so available, or (2) arrange to deprive yourself of the benefit of the patent license for this particular work, or (3) arrange, in a manner consistent with the requirements of this License, to extend the patent license to downstream recipients. "Knowingly relying" means you have actual knowledge that, but for the patent license, your conveying the covered work in a country, or your recipient's use of the covered work in a country, would infringe one or more identifiable patents in that country that you have reason to believe are valid.

    If, pursuant to or in connection with a single transaction or arrangement, you convey, or propagate by procuring conveyance of, a covered work, and grant a patent license to some of the parties receiving the covered work authorizing them to use, propagate, modify or convey a specific copy of the covered work, then the patent license you grant is automatically extended to all recipients of the covered work and works based on it.

A patent license is "discriminatory" if it does not include within the scope of its coverage, prohibits the exercise of, or is conditioned on the non-exercise of one or more of the rights that are specifically granted under this License. You may not convey a covered work if you are a party to an arrangement with a third party that is in the business of distributing software, under which you make payment to the third party based on the extent of your activity of conveying the work, and under which the third party grants, to any of the parties who would receive the covered work from you, a discriminatory patent license (a) in connection with copies of the covered work conveyed by you (or copies made from those copies), or (b) primarily for and in connection with specific products or compilations that contain the covered work, unless you entered into that arrangement, or that patent license was granted, prior to 28 March 2007.

Nothing in this License shall be construed as excluding or limiting any implied license or other defenses to infringement that may otherwise be available to you under applicable patent law.

12. No Surrender of Others' Freedom.

    If conditions are imposed on you (whether by court order, agreement or otherwise) that contradict the conditions of this License, they do not excuse you from the conditions of this License. If you cannot convey a covered work so as to satisfy simultaneously your obligations under this License and any other pertinent obligations, then as a consequence you may not convey it at all. For example, if you agree to terms that obligate you to collect a royalty for further conveying from those to whom you convey the Program, the only way you could satisfy both those terms and this License would be to refrain entirely from conveying the Program.

13. Use with the GNU Affero General Public License.

    Notwithstanding any other provision of this License, you have permission to link or combine any covered work with a work licensed under version 3 of the GNU Affero General Public License into a single combined work, and to convey the resulting work. The terms of this License will continue to apply to the part which is the covered work, but the special requirements of the GNU Affero General Public License, section 13, concerning interaction through a network will apply to the combination as such.

14. Revised Versions of this License.

    The Free Software Foundation may publish revised and/or new versions of the GNU General Public License from time to time. Such new versions will be similar in spirit to the present version, but may differ in detail to address new problems or concerns.

    Each version is given a distinguishing version number. If the Program specifies that a certain numbered version of the GNU General Public License "or any later version" applies to it, you have the option of following the terms and conditions either of that numbered version or of any later version published by the Free Software Foundation. If the Program does not specify a version number of the GNU General Public License, you may choose any version ever published by the Free Software Foundation.

    If the Program specifies that a proxy can decide which future versions of the GNU General Public License can be used, that proxy's public statement of acceptance of a version permanently authorizes you to choose that version for the Program.

    Later license versions may give you additional or different permissions. However, no additional obligations are imposed on any author or copyright holder as a result of your choosing to follow a later version.

15. Disclaimer of Warranty.

    THERE IS NO WARRANTY FOR THE PROGRAM, TO THE EXTENT PERMITTED BY APPLICABLE LAW. EXCEPT WHEN OTHERWISE STATED IN WRITING THE COPYRIGHT HOLDERS AND/OR OTHER PARTIES PROVIDE THE PROGRAM "AS IS" WITHOUT WARRANTY OF ANY KIND, EITHER EXPRESSED OR IMPLIED, INCLUDING, BUT NOT LIMITED TO, THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE. THE ENTIRE RISK AS TO THE QUALITY AND PERFORMANCE

OF THE PROGRAM IS WITH YOU. SHOULD THE PROGRAM PROVE DEFECTIVE, YOU ASSUME THE COST OF ALL NECESSARY SERVICING, REPAIR OR CORRECTION.

16. Limitation of Liability.

    IN NO EVENT UNLESS REQUIRED BY APPLICABLE LAW OR AGREED TO IN WRITING WILL ANY COPYRIGHT HOLDER, OR ANY OTHER PARTY WHO MODIFIES AND/OR CONVEYS THE PROGRAM AS PERMITTED ABOVE, BE LIABLE TO YOU FOR DAMAGES, INCLUDING ANY GENERAL, SPECIAL, INCIDENTAL OR CONSEQUENTIAL DAMAGES ARISING OUT OF THE USE OR INABILITY TO USE THE PROGRAM (INCLUDING BUT NOT LIMITED TO LOSS OF DATA OR DATA BEING RENDERED INACCURATE OR LOSSES SUSTAINED BY YOU OR THIRD PARTIES OR A FAILURE OF THE PROGRAM TO OPERATE WITH ANY OTHER PROGRAMS), EVEN IF SUCH HOLDER OR OTHER PARTY HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES.

17. Interpretation of Sections 15 and 16.

    If the disclaimer of warranty and limitation of liability provided above cannot be given local legal effect according to their terms, reviewing courts shall apply local law that most closely approximates an absolute waiver of all civil liability in connection with the Program, unless a warranty or assumption of liability accompanies a copy of the Program in return for a fee.

End of Terms and Conditions