METEOR Project: ash fall hazard footprints for Rungwe Volcano, Tanzania

Probabilistic ash fall hazard footprints have been produced for a Volcanic Explosivity Index (VEI; Newhall and Self, 1982) 2 and VEI 4 explosive eruption scenario at Rungwe Volcano for the METEOR project. Rungwe volcano in Southern Tanzania was chosen as it is one of the better-studied volcanoes in Tanzania, with a record of at least seven explosive eruptions within the last approximately 4000 years, including VEI 4 and 5 eruptions at approximately 2000 and 4000 year before present (yrs BP), respectively (Fontijn et al., 2010; Fontijn et al., 2011).

The model

Ash fall hazard footprints were generated using *TephraProb*, a freely available *Matlab* package developed to produce probabilistic hazard assessments for tephra fallout (Biass et al., 2016). *TephraProb* uses the *Tephra2* tephra dispersion model. *Tephra2* is an open source advection-diffusion model based on the work of Suzuki (1983) that describes diffusion, transport and sedimentation of tephra (ash) particles released from an eruption column (Connor et al., 2001; Bonadonna et al., 2005). It calculates the total mass per unit area (kg m^{-2}) of tephra accumulation at individual grid locations by solving a simplified mass conservation equation. The mass conservation equation takes into account the distribution of tephra mass in the eruption column and particle settling velocity, as well as horizontal diffusion within the eruption column and atmosphere after the particle has been ejected from the plume (Connor et al., 2001; Bonadonna et al., 2005; Connor and Connor, 2006). Eruption parameters are assumed to represent average conditions over the duration of the complete eruption (Connor and Connor, 2006).

TephraProb can be downloaded from here: https://github.com/e5k/TephraProb

The *Tephra2* source code can be downloaded from here: https://github.com/geoscience-community-codes/tephra2

Scenarios

We have chosen to model two eruption scenarios for Rungwe volcano based on past eruption history:

A VEI 2 scenario represents a relatively small eruption. Numerous small cones on the caldera and northwest flanks of Rungwe are indicative of such relatively small tephra-producing eruptions (Fontijn et al., 2010)

A VEI 4 explosive eruption scenario based on the Isongole Pumice eruption, which occurred approximately 2000 yrs BP. The Isongole Pumice eruption produced an eruption column of 17.5 km (above the vent) and a volume of 0.25 km^3 of tephra fallout (Fontijn et al., 2010). Based on this, the eruption was classified as a VEI 4, sub-Plinian event.

Input Parameters

The model requires a number of inputs representing the vent location, eruption column, wind, grain size and model parameters. These are described below, and the input parameters used for the modelling are given in Table 1.

The model was run with input parameter ranges for a number of eruption source parameters. The model was run probabilistically, 1000 times for each season (3000 in total), randomly selecting a wind file from a ten-year database for each run. We used different grid extents for the VEI 2 and 4 scenarios, with a larger grid for the VEI 4 scenario.

Input parameter	VEI 2 eruption scenario	VEI 4 eruption scenario	Notes
Vent			
Vent easting	569824	569824	UTM
Vent northing	8993539	8993539	UTM
Vent UTM zone	-36	-36	Negative in Southern Hemisphere
Vent height *(m asl)*	2953	2953	
Eruption			
Minimum total erupted mass *(kg)*	8.2×10^{8}	8.2×10^{10}	Volume multiplied by the bulk density
Maximum total erupted mass (*kg*)	7.38×10^{9}	8.1×10^{11}	Volume multiplied by the bulk density
Minimum column height *(m asl)*	1000*	11500**	*after Newhall and Self (1982)
Maximum column height (*m asl*)	5000*	21600**	**derived from relationship with volume (Jenkins et al., 2007)
Wind			
Number of wind files	16068	16068	Ten years, sampled 4-times daily
Wind start	01-Jan-2005 00:00:00	01-Jan-2005 00:00:00	
Winds per day	4	4	
Seasonality	1	1	Boolean 0/1. If enabled code will perform 3 runs: all; rainy season, dry season
Wind start rainy	April	April	
Wind start dry	December	December	
Grain Size Distribution			
Maximum grain size *(φ)*	-5	-5	Fontijn et al., 2011
Minimum grain size *(φ)*	4	4	Fontijn et al., 2011
Minimum median phi *(φ)*	-1	-1	Fontijn et al., 2011
Maximum median phi *(φ)*	-3	-3	Fontijn et al., 2011
Minimum standard deviation *(φ)*	2.5	2.5	Fontijn et al., 2011
Maximum standard deviation *(φ)*	1.5	1.5	Fontijn et al., 2011
Minimum aggregation	0.3	0.3	
Maximum aggregation	0.7	0.7	
Maximum aggregation diameter	5	5	Aggregation of material < 63 µm

Tephra2 model			
Eddy constant *(m^2 s^{-1})*	0.04	0.04	Eddy diffusivity term for small particles
Diffusion Coefficient *(m^2 s^{-1})*	3000	3000	Diffusion coefficient for large particles
Fall time threshold *(s)*	10000	10000	Threshold to allow fine particles to fall out
Lithic density *(kg m^{-3})*	2300	2300	Fontijn et al., 2011
Pumice density *(kg m^{-3})*	450	450	Fontijn et al., 2011
Integration steps	100	100	Number of steps column is discretised into
Alpha	1	1	Alpha and Beta are the plume shape parameters
Beta	0.7	0.4	60% tephra concentrated in top of plume for VEI4
			30% tephra concentrated in top of plume for VEI2

Table 1 Input parameters for TephraProb (see text for full descriptions)

Total erupted mass

We assumed a total erupted volume of 0.001 – 0.009 for a VEI 2 and 0.1 - 0.99 km^3 for a VEI 4 explosive event following the VEI classification of Newhall and Self (1982).

The bulk density of the deposits is estimated to be 820 kg/m^3 assuming 20:80 lithic to pumice clast ratio, using a clast density of 2300 kg/m^3 and pumice density of 450 kg/m^3 (Fontijn et al., 2011). The ranges of total erupted mass, calculated from the deposit density and volumes, for VEI 4 is 8.2×10^{10} to 8.1×10^{11} kg, and for VEI 2 is 8.2×10^{8} to 7.38×10^{9} kg.

Eruption Column Height

The minimum and maximum eruption column heights for a VEI 4 eruption was calculated from the erupted volume based on the empirical relationship derived by Jenkins et al. (2007) for explosive eruptive events:

$$\text{Height (km asl)} = 8.67.\log_{10}(\text{Volume in km}^3) + 20.2$$

The relationship assumes a sustained plume with no effect from wind on the plume height, therefore only works for larger magnitude eruptions. For a VEI 4 eruption, this gives an eruption column range of 11.5 to 20.16 km asl. Fontijn et al. (2010) calculated an eruption column height of 17.5 km above the event, equivalent to 20.5 km asl given a vent height of 2953 m asl, for the Isongole Pumice eruption. For a VEI 2 event, we assumed a column height of between 1 and 5 km asl, following the classification of Newhall and Self (1982).

Eruption Duration

Tephra2 assumes that the input parameters are representative for the average conditions over the peak eruption duration, and that most tephra is ejected in a short duration (few hours) explosive event (Connor and Connor, 2006).

Wind

TephraProb uses the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim global reanalysis dataset (Dee et al., 2011). We used a ten-year dataset from 1st January 2005 to 31st December 2014, sampled four-times daily (16068 wind files) to account for variations in wind conditions that could impact the ash fall footprint.

TephraProb has the option to run the model to reflect seasonal variation. When this option is enabled, the model will perform three runs: 1. All wind profiles; 2. Wind profiles for the rainy season; and 3. Wind profiles for the dry season. Winds in Southern Tanzania are predominantly easterlies and south-easterlies. From December to March, there is a stronger dominance of easterly winds with higher wind speeds (Fig. 1); therefore the model was run to take into account this seasonal variation. We modelled 1000 simulations each for 1. all wind profiles (year round), 2. wind profiles for December to March (dry), and 3. wind profiles for April to November (rainy).

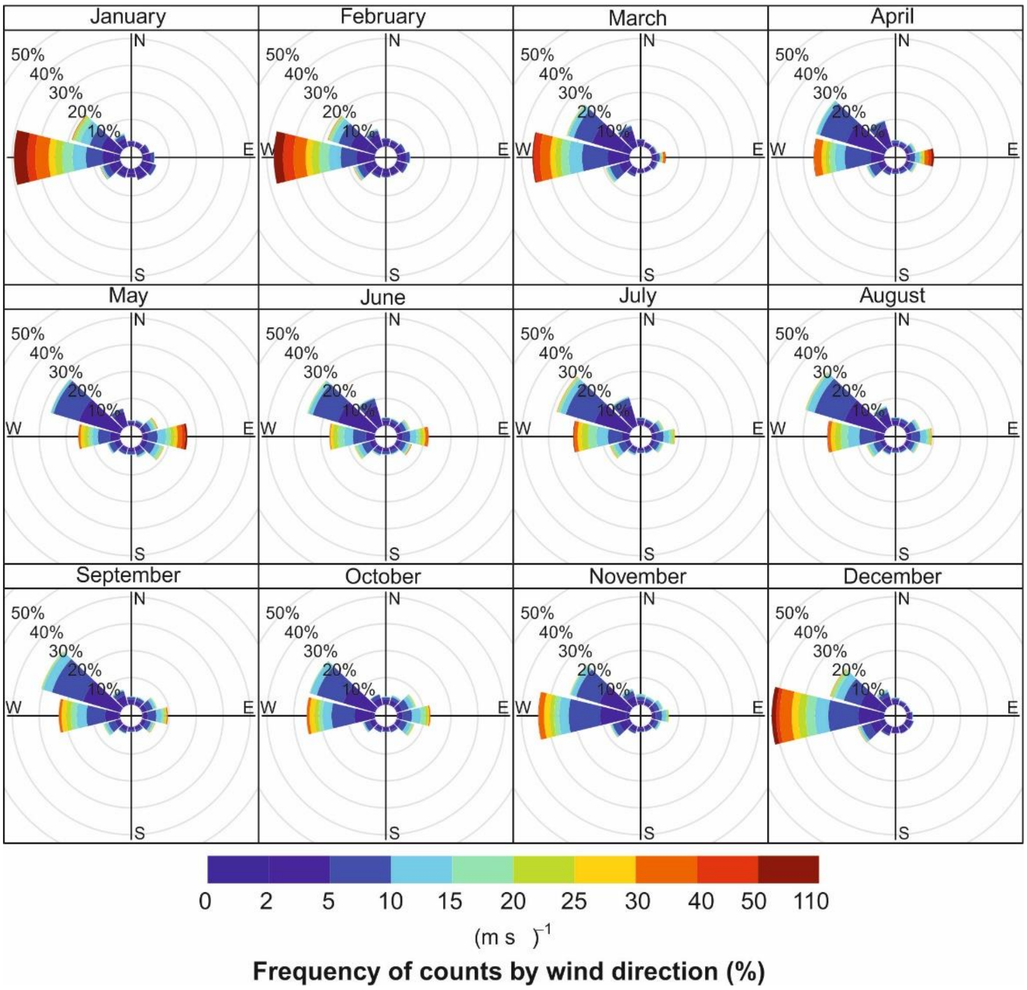

Figure 1. Ten-year ECMWF ERA-interim global reanalysis dataset for Rungwe from 1st January 2005 to 31st December 2014, separated by month to show seasonal variation in wind direction. Coloured bars show the direction the wind is blowing, colours represent the wind speed, and the length of the bar represents the frequency of counts by wind direction (%)

Grain Size Distribution

A normal distribution was used with minimum and maximum bounds of 4 phi (63 microns) and -5 phi (32 mm), respectively, with a median between -1 and -3 phi and standard deviation of 1.5 to 2.5 phi, following the total grain size distribution determined by Fontijn et al. (2011) for the Rungwe Pumice. It was assumed that finer material would either fall as aggregates (input aggregation factor) captured within these grain size bounds, or be dispersed much further than the ash fall footprints being simulated. Based on the similarity between the Isongole Pumice and the Rungwe Pumice deposit characteristics (Fontijn et al., 2010), and given the lack of grain size data for the Isongole Pumice deposit, it was deemed appropriate to use the Rungwe Pumice derived grain size distribution.

Eddy Constant

The eddy diffusivity term for small particles, which is 0.04 m^2/s.

Diffusion Coefficient

The horizontal diffusion coefficient for large particles. A value of 3000 was used, consistent with the GFDRR/DfID Challenge Fund Project (Loughlin et al., 2018).

Fall Time Threshold

Threshold to allow fine particles to fall out. A value of 10000 was used, consistent with the GFDRR/DfID Challenge Fund Project (Loughlin et al., 2018).

Particle Density

Lithic density of 2300 kg/m^3 and pumice density of 450 kg/m^3 (Fontijn et al., 2011).

Integration Steps

Tephra2 models the fall of particles as they are transported away from the plume and deposited on the ground. In order to take into account variations in wind, flow regime, diffusion etc., the eruption column and atmosphere are discretised into integration steps. Previous studies have shown that more than 100 steps has no impact on the tephra fallout estimates at the grid locations (Connor and Connor, 2006).

Plume model (alpha & beta parameters)

The alpha and beta parameters describe the mass distribution of tephra within the plume:

If $\alpha=\beta=1$, then particles are dispersed uniformly within the plume;

If $\alpha>\beta$, then particles are concentrated in the top of the plume;

If $\alpha<\beta$, then particles are dispersed in the bottom of the plume.

For a less powerful, smaller magnitude VEI 2 eruption, we assume deposition from the majority of the whole plume, therefore assume only 30% of particles are concentrated in the top of the plume: $\alpha=1$, $\beta=0.7$. For a VEI 4, sub-Plinian type eruption, we assume 60% of particles are concentrated in the top of the plume: $\alpha=1$, $\beta=0.4$.

Outputs

TephraProb generates three types of output text files for each tephra accumulation threshold (from 0.01 to 1000 kg/m^2) for plotting probability maps in different programs: GMT, Matlab and GIS.

Outputs of 1, 10 and 100 kg/m^2 tephra accumulation thresholds were selected, which equate to thicknesses of approximately 0.1, 12 and 120 cm given the bulk deposit density of 820 kg/m^3. Thicknesses of as little as 1 mm ash fall can cause transport problems, damage to electrical and mechanical components, blockages and clogging of water intake structures and infiltration systems (Jenkins et al., 2015).

Each threshold has two datasets for the two seasons modelled: December to March (dry) and April to November (rainy). *Note that* TephraProb *automatically names the two seasons dry and rainy. In Tanzania, these months were chosen to reflect the variability in wind conditions and do not necessarily reflect the dry and rainy seasons*.

The ASCII text files for conversion to RASTER have been saved in:
<W:\Teams\EPOM\METEOR\Data\WP6_Multihazard_impact\Data\Tanzania\Ash_hazard\Tephra\TephraProb\Raster\ASCII_files>

Within ArcMap10.3.1, these have been converted to raster datasets and saved here: <W:\Teams\EPOM\METEOR\Data\WP6_Multihazard_impact\Data\Tanzania\Ash_hazard\Tephra\TephraProb\Raster>

GIS point shapefiles have been generated for each raster, which are saved in the same folder.

The projection used is UTM, WGS1984, Southern hemisphere zone 36S.

An ArcGIS project with the raster data and shapefiles is here: <W:\Teams\EPOM\METEOR\Data\WP6_Multihazard_impact\Data\Tanzania\Ash_hazard\Tephra\Ash_fall_hazard_probability_VEI4.mxd>

The TephraProb output maps generated in Matlab have been saved as jpeg files here: <W:\Teams\EPOM\METEOR\Data\WP6_Multihazard_impact\Data\Tanzania\Ash_hazard\Tephra\TephraProb\Matlab_Maps>

Sources of Uncertainty

Although Rungwe is one of the best studied of the Tanzanian Holocene volcanoes, knowledge of its eruption history is still limited; therefore, any modelling of potential future volcanic ash fall hazard is subject to high degrees of uncertainty.

We have modelled a VEI 2 and VEI 4 explosive eruption scenario. This is not a forecast and should not be considered a most likely scenario. A future eruption is unlikely to have exactly the source parameters and wind conditions modelled here. There are a number of factors, which can have a strong influence on the area impacted by ash fall, for example, a finer particle size distribution will lead to a larger area being impacted. Particle size can be strongly influenced by magma composition or the presence of water; therefore, the explosive event does not necessarily need to be larger magnitude than modelled here to have a greater ash fall footprint. The resultant ash fall footprints are for communication purposes only and should not be considered hazard maps for use in practise for planning or preparedness.

The volcanic ash hazard to aviation and from wind remobilisation of ash fall deposits is not accounted for within our modelling. The hazard from airborne ash is likely to affect much larger areas, and hazard from ash remobilisation can continue for months, years or even decades after the event (e.g. Wilson et al., 2011).

Volcanic eruptions can last from a few hours to days, weeks, months and years. Based on global analysis, the median duration of an eruption is 7 weeks (Simkin and Siebert, 2000). Typically, an eruption comprises volcanic unrest prior to the onset of explosive activity and unrest that can continue after the explosive phase. Many explosive eruptions have multiple explosive events or phases, each lasting minutes to hours. *Tephra2* assumes that the input parameters are representative for the average conditions over the peak eruption duration, and that most tephra is ejected in a short duration explosive event (Connor and Connor, 2006).

The bulk density of the deposits was estimated to be 820 kg/m^3 assuming 20:80 lithic to pumice clast ratio, using a clast density of 2300 kg/m^3 and pumice density of 450 kg/m^3 (Fontijn et al., 2011). Fontijn et al. (2010) report up to 30% lithics in the Isongole Pumice in samples collected within 10 km of the vent. As the data are from proximal deposits, it is likely that this lithic proportion is overestimated for the entire deposit; therefore, a 20:80 lithic to pumice ratio was used for the model. It should be noted, that this may still overestimate the proportion of lithics.

As well as uncertainties related to the input parameters, there are uncertainties related to the model itself. Due to the complexities involved in modelling atmospheric conditions, *Tephra2* does not take into account horizontal changes in wind conditions away from the vent. A number of assumptions have to be made on diffusion and particle fallout, which will be different for each explosive event depending on atmospheric conditions, mass eruption rate, particle size and particle density.

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