Research Networking Programmes

Exchange Visit Grant

Scientific Report

The scientific report (WORD or PDF file - maximum of eight A4 pages) should be submitted online within one month of the event. It will be published on the ESF website.

Proposal Title: Long-term Probabilistic Volcanic Hazard Assessment for tephra fallout in Reykjavik through a multi-volcano approach

Application Reference N°: 4681

1) Purpose of the visit

The idea behind this proposal was to prepare the input needed to perform a Probabilistic Volcanic Hazard Assessment (PVHA) for tephra fallout to the target area which includes Reykjavik, the capital and the cultural and economic center of Iceland, and the Keflavik international airport, located about 50 km south west of Reykjavik, in the Reykjanes peninsula. PVHA represents an important input to volcanic risk analysis and risk mitigation planning and allows the quantification of the volcanic hazard together with its uncertainties arising from the natural variability of volcanic processes (aleatory uncertainty) and from our incomplete knowledge (epistemic uncertainty). In particular, differently from the scenario-based hazard assessment, in which only one or a few representative scenarios are usually selected, PVHA potentially includes all the possible scenarios, weighted with their probability of occurrence.
The proposed PVHA analysis will be performed with the innovative idea of using a sort of volcanic multi-hazard approach focused on the target area instead of on the volcanic source. In practice, we will homogeneously quantify the hazard due to the main hazardous volcanoes that could pose a tephra fallout threat for the municipality of Reykjavik and the Keflavik airport. This will allow to compare and hierarchically rank the tephra fallout risk among both all the considered volcanoes and, possibly, other kinds of risk.

The scope of the visit was mainly focused on collecting all the available data and information, and, together with Dr. Sara Barsotti (IMO, expert of tephra modeling) and professor Magnús Tumi Guðmundsson (University of Reykjavik, expert of Icelandic volcanism and volcanic systems) to translate such data into input to the PVHA analysis. In particular, the main specific objectives are listed here below:

1. Define the extension of the considered target area and the grid resolution on which the results will be provided in the form of hazard curves or maps.

2. Identify the most significant Icelandic volcanic sources whose tephra fallout could affect the selected target area, depending on their eruptive behavior, their eruptive history or their distance from the target.

3. For each volcano: i) collect available data from the volcano's history and define an eruptive catalog which is reasonably complete; ii) define the possible vent locations; iii) define a range of sizes/styles of possible eruptions and define a representative eruptive scenario for each size/style. The latter is needed to perform the tephra dispersal modeling; iv) compute frequencies: of eruptions, of eruptions from the different vent positions, of eruptions of a specific size given there is an eruption; v) decide whether the vent position might affect the size. This is reasonable in some conditions, for example if some vent locations are under water or under glaciers (different eruptive behavior).

4. For tephra modeling: i) define the input parameters (for each volcano) for every representative eruption of the various sizes/styles; ii) define a set of statistically significant wind profiles for simulations.

2) Description of the work carried out during the visit

2.1 Introduction

Tephra fallout is one of the major volcanic hazard, even though the magma is mainly basaltic and effusive eruptions in Iceland should be dominant. Differently, the presence of glaciers over many Icelandic volcanic systems often gives rise to phreatomagmatic activity. Existing tephra deposits are very few and mainly located in the south of Iceland, but some traces can be found also in Reykjanes region and Snæfells peninsula. Moreover, these deposits are driven by the wind direction that can change with both altitude and season, making impossible to predict a priori where the tephra cloud will be blow out during the next eruptions.

The selected volcanoes for this first multi-source tephra fallout PVHA are Katla, Hekla, Grímsvötn, Reykjanes and Snæfellsjökull (Figure 1). The first three (Katla, Hekla and Grímsvötn) are those with the higher frequency of eruption in the last 1100 years, when the Iceland settlement begun, and, despite their distance, they can potentially affect the target area with tephra fallout under unfavorable winds. The latter two (Reykjanes and Snæfellsjökull) are the closest ones with respect to the considered target area that can produce tephra. Eyjafjallajokull volcano, even though created a huge ash cloud dispersion during its last eruption in 2010 has been not considered here because it doesn't match our double criterion based on the history and the distance from the target. However, this selection is not definitive, meaning that further volcanoes can be considered later on. Indeed, any PVHA is calculated independently for each volcanic system and the results from all the PVHAs can be combined at the end. Even though most of the results obtained in these four weeks are focused on Katla, some of them can be generalized to the other volcanoes and will be described in the next sections. Nevertheless some peculiarities concerning the latter ones will be examined after my coming back.

2.1.1 Katla

Katla is a volcanic complex system consisting of both a central conic structure and a fissure expanding NE respect with the central volcano. The central volcano is partially overlaid by the Myrdalsjokull glacier and, in particular, its caldera is completely covered by a thick layer of ice all over the year. The Myrdalsjokull glacier is usually divide into three sectors, called Entlujokull (En), Kotlujokull (Ko) and Solheimajokull (So) on the basis of the routes followed by the jokulhlaups (Icelandic term meaning glacial outburst flood due to geothermal or volcanic activity beneath the ice). The number of known events in last 1100 years is 20, all of them being explosive (included the major eruption in 934-938, which was both effusive and explosive). No pure effusive eruptions have been observed in this time span. All the explosive eruptions occurred in Katla in the last 1100 years can be associated to the central caldera of the conic structure, except for the very large eruption occurred in 734-738 AD. The latter involved the entire Katla system, both the central volcano and the fissure in an extraordinary huge eruption. Since the Katla's eruptions occurred under the glacier, they generated jokulhlaups. All these 20 eruptions have been associated to a jokulhlaup's flood deposit (Eliasson et al., 2006) and this has allowed to argue a more detailed spatial distribution about the location of the vent of each eruption. According to Eliasson et al. (2006), past eruptions have been occurred in Ko glacier. A particular note is needed for the very large Eldja's eruption, where the jokulhlaups' deposits include both Ko and So but very likely the eruptions interested many vents along all the volcanic structure, including the central volcano and the fissure.

2.1.2 Hekla

The Hekla volcano is a peculiar ridge-shaped stratovolcano as a consequence of several repeated eruptions that occur along its about 5 km long fissure extending along southwest/northeast direction across the summit caldera. Hekla experienced 23 eruptions in the last 800 years, whose 18 occurred in the central volcano with explosive behavior and the remaining 5 was effusive eruptions occurred in the fissures (Thordarson and Larsen, 2007). More detailed analysis on the location of past events needs to be performed.

2.1.3 Grímsvötn

The Grímsvötn (or Grímsvötn/Laki) system is the most active in Iceland in terms of eruptive frequency with about 65 known eruptions in the last 800 years. It is formed by a 50 km^2 ice-covered central caldera with persistent geothermal activity and by a fissure extending 80 km SE with respect the caldera. Only the last about 30 km of the fissure are ice free, corresponding to the Laki line of craters. Here the analysis of the past events is at a preliminary stage.

2.1.4 Reykjanes

The Reykjanes volcanic system is located at the westernmost region of the homonymous peninsula and is often associated with the contiguous Svartsengi system. The Reykjanes is the only system that does not present a central structure and its behavior is purely effusive, but its southernmost part is submerged for 9 km and tephra fallout can be produced by phreatic/phreatomagmatic explosions due to the magma-water interaction. According to the current draft catalogue of the ongoing FUTUREVOLC project, 6 explosive eruptions have been observed in the last 1100 years.

2.1.5 Snæfellsjökull

The Snæfellsjökull lays in the westernmost area of Snæfellsnes peninsula and is composed by a central shape stratovolcano covered by a glacier on the summit caldera and by a small fissure. No eruptions have been observed in the last 1100 years.

2.2 Input to BET_VH

The Bayesian Event Tree for Volcanic Hazard (BET_VH) is a statistical tool aimed to calculate the long-term Probabilistic Volcanic Hazard (PVHA) of a wide range of volcanic hazardous phenomena (i.e., lava flows, tephra fallout, pyroclastic flows, lahars, etc.) through a Bayesian event tree model (Marzocchi et al., 2010). BET_VH goes beyond the limits of scenario-based hazard assessment, by potentially combining all the possible eruptive scenarios with the weight of their probability of occurrence and quantifying the aleatory and epistemic uncertainties. For each node a probability is calculated by means of a Bayesian approach, meaning that a prior probability distribution (usually coming from theoretical models) and information from past data are statistically combined together to obtain a posterior probability. The tool has been applied to produce a PVHA for base surge impact in Auckland Volcanic Field, New Zealand (Sandri et al., 2012) and to accomplish a probabilistic volcanic multi-hazard assessment at Arequipa, Peru, by considering the hazard posed by several different phenomena associated to the next eruption of El Misti volcano (Sandri et al., 2014). The event tree has been recently improved by introducing the calculation of hazard curves (Sandri et al., in preparation) and the new tool can calculate, in a given area and in a given time frame, the probability to overcome a set of given thresholds for the considered intensity measure with different level of confidence (best guess and percentiles). This feature is included in the very recent new software implementation of BET_VH, called PyBetVH and equipped with a Graphical User Interface (GUI) which allows users to handle the PVHA results by interactively visualizing the hazard curves together with the corresponding hazard and probability maps (Tonini et al., 2014). This new version will update the current BET_VH version hosted on the VHub cyber-infrastructure platform at https://vhub.org/resources/betvh.

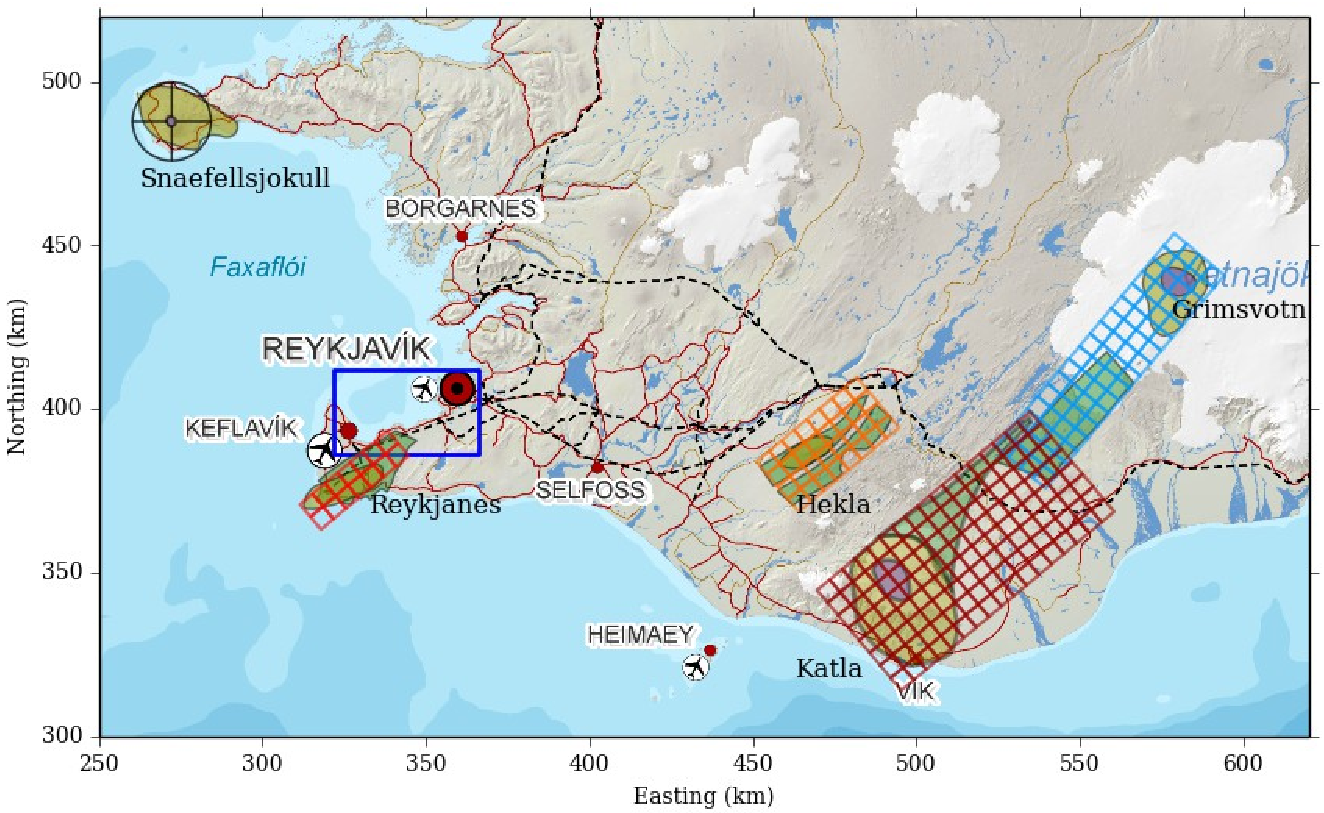

Figure 1: Position of the five most “significant” sources of tephra fallout hazard for the considered target area (blue rectangle) and spatial representation of vent locations for each selected volcano. We based our geometric representations on the available information on the geological boundary for each volcanic system. Snæfellsjökull is the only system that we decided to approximate with a central conic structure.

2.2.1 Nodes 1-2-3: probability of eruption

Nodes 1-2-3 represent the probability of experiencing an eruption in the next forecast time window *Dt*, here set equal to 10 years. As regards the probability density function for this node, for all the volcanoes we assumed the maximum ignorance as prior probability (P = 0.5) and we used the available past data to better assess the aleatory uncertainty and to reduce the epistemic one. The procedure consists of selecting a reasonably complete catalogue of historical events for each volcano. Here we decided to be coherent with the approach followed to compile the catalogue in the frame of FUTUREVOLC project, currently in progress, and we considered a time frames corresponding to the last 1100 years, when Iceland was settled.

2.2.2 Nodes 4-5: vent location and style/size of eruption

These nodes represent the conditional probability to experience a specific eruptive scenario, that is, an eruption from a given vent position (Node 4) and of a given size (Node 5). As regards Node 4, no theoretical model exists to determine the spatial probability of vent opening, but some assumption can be made on the basis of the knowledge of each specific volcano. For example, it is a common assumption to assign a much higher probability to vents located inside the caldera of central volcanoes. Volcanologists usually assign return period much shorter for such vents respect to lateral vents and this can be used as information to set our prior distribution. This assumption works well for four of the five volcanic systems here considered, except for Reykjanes, where we assign the same prior probability to all vents through a uniform distribution. We represent each volcanic system through a geometric scheme of possible vent locations as shown in Figure 1. The analysis for Node 4 has been completed for Katla volcano only (see Figure 2). With regards Node 5, we have defined 5 possible styles of eruption, including one effusive style and four explosive styles with different sizes (small, moderate, large, very large) in terms of tephra volume erupted. The styles/sizes are homogeneous among all the volcanic systems, even though not all the volcanoes are represented by all the eruptive styles/sizes (Table 1).

Style/Size	**Katla**	**Hekla**	**Grímsvötn**	**Reykjanes**	**Snæfellsjökull**
Effusive	Yes	Yes	Yes	Yes	Yes
small (< 0.1 km3)	Yes	Yes	Yes	Yes	Yes
medium (0.1-0.5 km3)	Yes	Yes	Yes	Yes	Yes
large (0.5-1.0 km3)	Yes	Yes	Yes	No	Yes
very large (> 1.0 km3)	Yes	Yes	No	No	No

Table 1. List of eruptive style/sizes considered for each volcanic system.

The presence of the glacier or water over a vent is an important factor for the eruptive style because the magma-ice or magma-water interactions are a trigger for phreatomagmatic explosive eruptions. All the considered volcanoes are partially covered by a glacier on top, except for Reykjanes, which has some submerged vents in the southwestern. As a consequence, we assign different behaviors to vents overlaid by ice or water with respect vents on land. At this preliminary stage, we decide to assign the same behavior to magma-ice and magma-water interactions in terms of probabilities, but a more detailed analysis will be made to better address this not well-known issue. Here, we assumed that for vents under glacier/water, a pure effusive eruption is very unlikely, being the presence of overlaying ice/water a strong factor to have explosive eruptions. Therefore, for these vents, we set P=0.05 to the effusive style and we use the empirical power law defined by Newhall and Hobblit (2002) to assign the probability of occurrence to the four explosive classes. Differently, for the vents uncovered by ice/water, effusive and eruptive style are considered to be equally probable, so we assigned P=0.5 to effusive eruptions and we assigned the probabilities to the explosive styles through the same Newhall and Hobblit's law. For both cases the total probability must be equal to 1.0. Prior probabilities and known past data for each eruptive style are provided in Table 2 and 3.

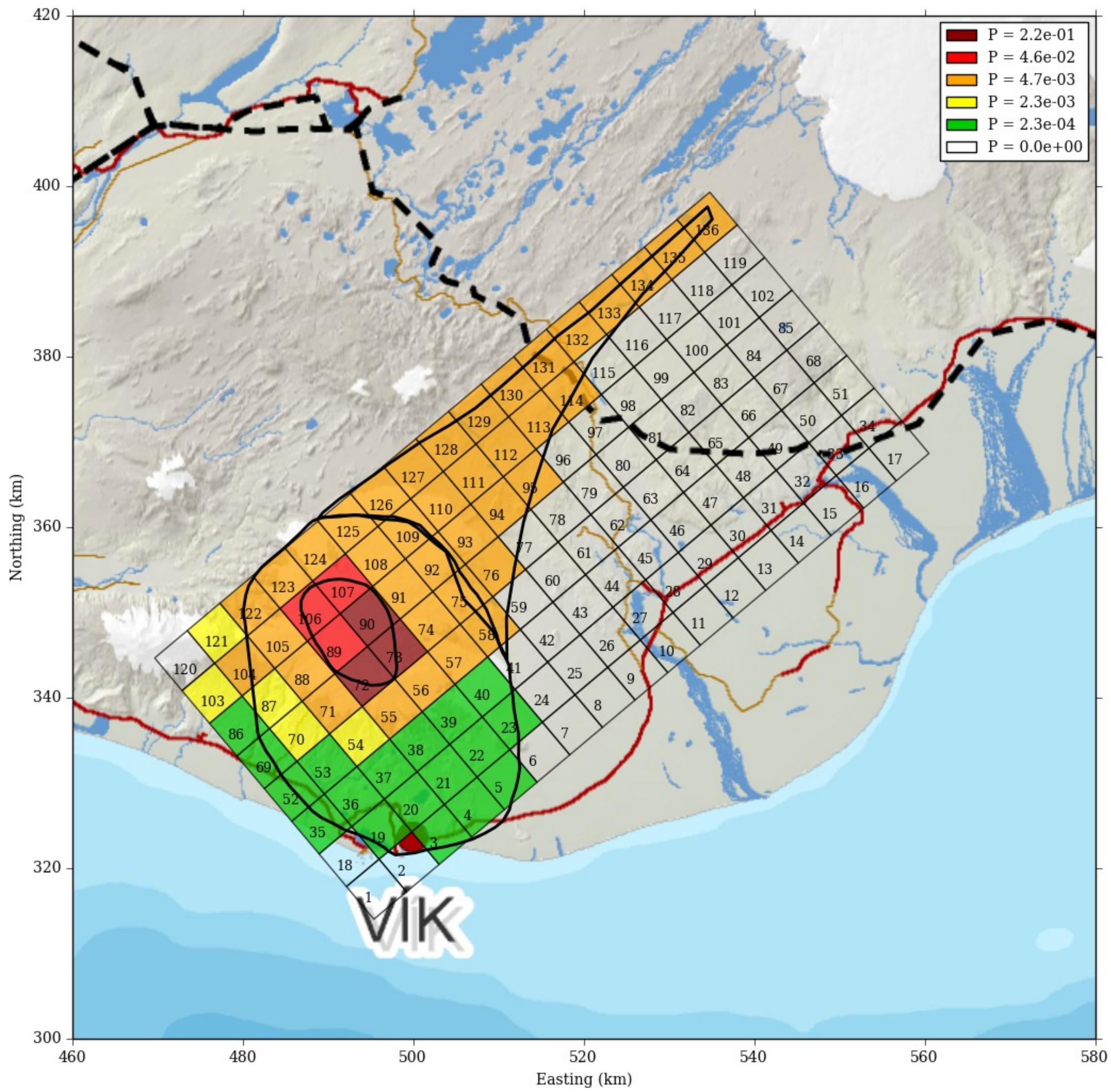

Figure 2: Geometric grid representation of opening vents for the Katla system and corresponding prior probabilities weighted on the basis of the estimated return time after Guðmundsson and Högnadóttir (2006). No-colored cells are not considered as possible new opening vent and we set P = 0. Ko glacier is represented by cells 72, 73 and 90.

	Prior Probability (covered by glacier/water)	**Prior Probability (no covered by ice/water)**
Effusive	0.05	0.5
small (< 0.1 km3)	0.792	0.417
medium (0.1-0.5 km3)	0.087	0.046
large (0.5-1.0 km3)	0.045	0.023
very large (> 1.0 km3)	0.026	0.014

Table 2. Prior probability for Eruptive style/sizes is assigned assuming that the eruptive behavior between vents under and off the glacier is different.

Style/Size	Katla	Hekla	Grímsvötn	Reykjanes	Snæfellsjökull
small (< 0.1 km3)	9	5	-	4	0
medium (0.1-0.5 km3)	5	11	-	2	0
large (0.5-1.0 km3)	5	1	-	NC	0
very large (> 1.0 km3)	1	1	NC	NC	NC

Table 3. Number of past eruptions for each explosive size and for each volcanic system in the common time frame of the last 1100 years. Not considered sizes are labeled NC. For Grímsvötn, this stage is not ready yet.

2.2.3 Nodes 6-7-8: tephra production and impact in the target area

At node 6 the probability of having tephra fallout given an eruption in a given location with a given style/size is calculated. The probability at this node is essentially controlled by the occurrence of an eruption with explosive behavior: indeed, explosive eruptions of any size produce tephra fallout, thus we set $P = 1$ for all the explosive sizes. On the other hand, pure effusive styles do not produce any tephra fallout and, for such a style, we simply set $P = 0$. Nodes 7 and 8 represent the probability that a set of intensity thresholds is exceeded in any grid point of the target area. The result is visualized by means of hazard curves, hazard maps and probability maps. Node 7 and 8 will be calculated once all the simulation for tephra modeling will be performed.

3. Tephra modeling: definition of representative scenarios

The tephra dispersal, transport and deposition will be modeled through the VOL-CALPUFF code (Barsotti et al., 2008). This code is a hybrid model in which the plume rise phase is described with a Eulerian approach (Bursik, 2001), whereas the ash cloud transport is solved in a Lagrangian framework. Due to its numerical formulation it is particularly suited for multiple runs still keeping a limited time consumption (Barsotti et al., 2010). The code allows the description of the plume rising phase in order to reproduce the action of the wind on the eruptive column bending. Further the pyroclasts injected in the atmosphere abandon the column at different altitudes as a function of their different sizes and densities. The material lost from the column is transported by the main wind field and settle due to gravity. The transport of ash cloud occurs in a 3D and time-dependent atmosphere where many parameters are taken into consideration; i.e. wind field, temperature profile, humidity, precipitation. The meteorological data set that will be used is ten years, for the period 1980-1990, available at the ERA-INTERIM archive provided by the European Center for Medium-Range Weather Forecasts (www.ecmwf.int). A preliminary analysis of the statics of this data set has been produced to highlight the wind field variation with altitude and spatial location (Figure 3). The variability of the wind field is indeed one of the most important factors for long-term tephra fallout hazard. The panels in Figure 3 show that at high levels in the atmosphere the predominant direction of the wind is toward NE, but the likelihood of having wind blowing toward the west (and, as a consequence, toward Reykjavik and surroundings) increases at lower altitudes. This implies that for mild eruptions, with column height of a few km, the likelihood of an ash cloud drifted toward W could be remarkable. The meteorological data will be refined in time and space with the meteorological processor CALMET and will be then used as input to the dispersal code VOL-CALPUFF. A large number of runs will be performed by using different wind profiles randomly sampled from the meteorological data set covering the last decades. By grouping the wind profiles by seasons it will also be possible to study the seasonal variation of the hazard.

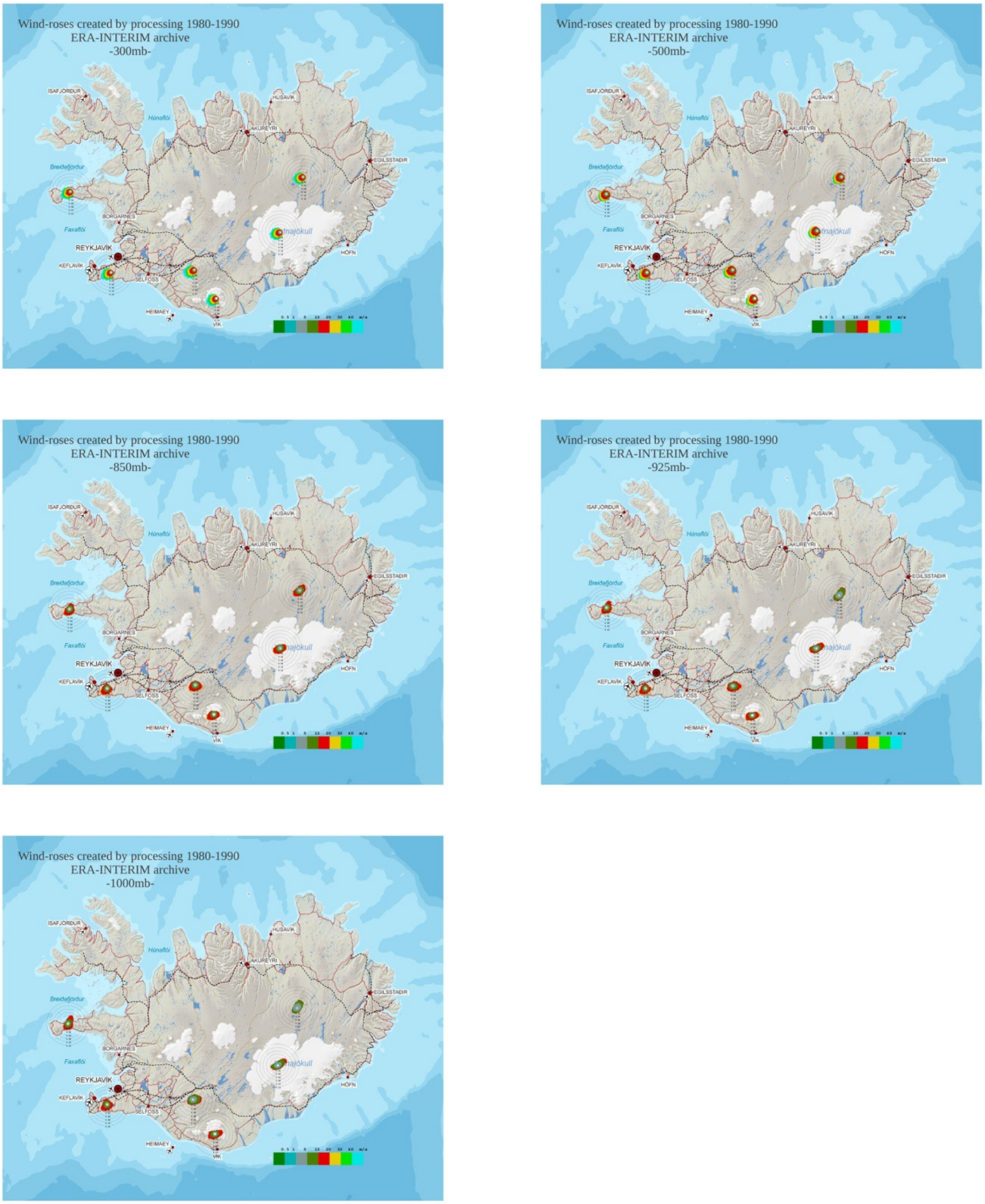

Figure 3: Wind roses produced using the ERA-INTERIM archive for the period 1980-1990. Wind roses have been produced for different pressure levels and different locations across the country. The locations of the main volcanic system considered in this study have been considered.

In order to reproduce the entire range of eruptive scenarios, it is needed to define the input parameters characterizing each eruption "size". The tephra volume, usually well constrained by field studies, and the maximum column height estimation are two parameters often available for historical eruptions. Using these two parameters, and playing with plume model results, we will try to estimate the main source parameters (mass flow rate and duration) that could be in a reasonable agreement with the observed data. On the other hand, the explosive behavior of the Icelandic volcanoes, mostly due to their hydrological component, does not fit with the commonly used plume theory models, where the uplift of the mixture is mainly due to the initial gas thrust and contrast of density with the atmospheric air. In order to face with this limitation of the code, we have performed a sensitivity analysis of plume model results to the entrainment coefficient in order to match the observed column height and the estimated mass flow rate. We found that an ad-hoc solution is to set the entrainment parameter α equals to 0.09. This calibration has been based on matching mass flow rate (4.2×10^6 kg/s) and column height (15 km) for the eruption occurred at Katla on 1918. A predefined grain-size distribution will be assumed in input, but we will not consider its variability across the ranges in eruptive intensities. The next steps will be to define the input parameters for all the eruptive scenarios reported in Table 2 and then run all the simulations.

References

Barsotti, S., A. Neri, and J. S. Scire (2008) The VOL-CALPUFF model for atmospheric ash dispersal: 1. Approach and physical formulation, Journal of Geophysical Research, 113, B03208, doi:10.1029/2006JB004623

Barsotti, S., D. Andronico, A. Neri, P. Del Carlo, P. J. Baxter, W. P. Aspinall, and T. Hincks (2010) Quantitative assessment of volcanic ash hazards for health and infrastructure at Mt. Etna (Italy) by numerical simulation, J. Volcanol. Geotherm. Res., 1-2, 192, doi:10.1016/j.jvolgeores.2010.02.011

Bursik, M. I. (2001) Effect of wind on the rise height of volcanic plumes, Geophys. Res. Lett., 28, 3621–3624.

Elíasson J., Larsen G., Guðmundsson M. T. and Sigmundsson F. (2006) Probabilistic model for eruptions and associated flood events in the Katla caldera, Iceland. Computational Geosciences, 10, 179-200.

Guðmundsson M. T. and Högnadóttir Þ. (2006) Ísbráðnun og upptakarennsli jökulhlaupa vegna eldgosa í Kötluöskju og austanverðum Mýrdalsjökli, Jarðvísindastofnun Háskólans, RH-02-2006 (in Icelandic).

Marzocchi W., Sandri L., Selva J., (2010) BETVH: a probabilistic tool for long-term volcanic hazard assessment, Bull. Volcanol., 72, 705-716, DOI: 10.1007/s00445-010-0357-8.

Newhall C. G. and Hoblitt R. P. (2002) Constructing event trees for volcanic crises. Bull Volcanol 64:3–20. doi:10.1007/s004450100173.

Sandri L., Jolly G., Lindsay J., Howe T., Marzocchi W., (2012) Combining long- and short-term probabilistic volcanic hazard assessment with cost-benefit analysis to support decision making in a volcanic crisis from the Auckland Volcanic Field, New Zealand, Bull. Volcanol., 74, 705–723, DOI: 10.1007/s00445-011-0556-y.

Sandri L., Selva J., Costa A., Tonini R., Foch A., Mecedonio G., Exploring the full natural variability of eruption sizes within probabilistic hazard assessment of tephra dispersal, in preparation.

Sandri L., Thouret J.-C., Costantinescu R., Biass S., Tonini R., (2014) Long-term multi-hazard assessment for El Misti volcano (Peru), Bulletin of Volcanology, 76:771, doi: 10.1007/s00445-013-0771-9.

Selva J., Costa A., Marzocchi W., Sandri L., (2010) BETVH: exploring the influence of natural uncertainties on long-term hazard from tephra fallout at Campi Flegrei (Italy), Bull. Volcanol., 72, 717-733, DOI: 10.1007/s00445-010-0358-7.

Thordarson T. and Larsen G. (2007) Volcanism in Iceland in historical time: Volcano types, eruption styles and eruptive history, Journal of Geodynamics, 43, 118–152

Tonini R., Sandri L., Thompson M. A. (2014) PyBetVH: a Python tool for probabilistic volcanic hazard assessment and for generation of Bayesian hazard curves and maps, submitted to Computers & Geosciences.

3) Description of the main results obtained

The results have been described in the previous section, together with the description of the work and they are summarized here below:

1. We exactly defined the target grid where to perform our multi-source PVHA analysis and selected the most significant hazardous volcanoes for tephra fallout for that target area.
2. We discretized the selected volcanic systems in terms of all possible vents location on the basis of the current knowledge of each volcano and we defined the possible styles/sizes of eruptions for the selected volcanoes.
3. We assigned prior probabilities to the first 6 Nodes of BET_VH, by using all the current available information and we analyzed the history of each volcano in order to assign the location and size of past eruptions when possible and the corresponding uncertainties. This task has not yet been completed for all the selected volcanoes, but the method we developed for Katla can be applied to the other volcanoes and, moreover, many results obtained for Katla system can be used directly for the others (e.g., styles/size definitons and representative scenarios)
4. We set the VOL-CALPUFF tephra fallout code for our PVHA analysis, by setting specific input parameters for the considered volcanoes and the modeling stage is now in progress

4) Future collaboration with host institution (if applicable)

Future collaboration is strongly required to accomplish the final goal of the work, which is to provide hazard curves and maps for tephra fallout in the selected target area. Once that the whole set of tephra dispersal simulations will be concluded, their results will be used to calculate the exceedance probability as function of the considered intensity measures (tephra ground loading and PM10 concentration) in the next 10 years in all the points used to described the target area.

5) Projected publications / articles resulting or to result from the grant (ESF must be acknowledged in publications resulting from the grantee's work in relation with the grant)

The overall work will be ready to be submitted to peer-reviewed journals and international conferences as soon as the full set of tephra simulations will be ready and used as input to BET_VH as all the other data. The possibility to publish or at least present the most important preliminary results is under evaluation as well.

6) Other comments (if any)

During my visit, the Bardarbunga unrest started, moving most of resources and priorities to the tracking of the forthcoming eruption occurred a couple of days after my departure. This has required a lot of efforts for the Icelandic volcanological community and, in particular, for IMO which is the main responsible for operational volcanic hazard activities connected to Icelandic civil protection.