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Key Points:

- We applied PyBetUnrest during a VUELCO volcanic unrest simulation exercise in Dominica, West Indies
- Probabilities (and associated uncertainties) of unrest and eruption were deliberated in "real time"
- The probabilities were often discounted by the Scientific Team, revealing interesting crisis communication challenges

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Application of the probabilistic model BET_UNREST during a volcanic unrest simulation exercise in Dominica, Lesser Antilles

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Abstract We report on the first "real-time" application of the BET_UNREST (Bayesian Event Tree for Volcanic Unrest) probabilistic model, during a VUELCO Simulation Exercise carried out on the island of Dominica, Lesser Antilles, in May 2015. Dominica has a concentration of nine potentially active volcanic centers and frequent volcanic earthquake swarms at shallow depths, intense geothermal activity, and recent phreatic explosions (1997) indicate the region is still active. The exercise scenario was developed in secret by a team of scientists from The University of the West Indies (Trinidad and Tobago) and University of Auckland (New Zealand). The simulated unrest activity was provided to the exercise's Scientific Team in three "phases" through exercise injects comprising processed monitoring data. We applied the newly created BET_UNREST model through its software implementation PyBetUnrest, to estimate the probabilities of having (i) unrest of (ii) magmatic, hydrothermal or tectonic origin, which may or may not lead to (iii) an eruption. The probabilities obtained for each simulated phase raised controversy and intense deliberations among the members of the Scientific Team. The results were often considered to be "too high" and were not included in any of the reports presented to ODM (Office for Disaster Management) revealing interesting crisis communication challenges. We concluded that the PyBetUnrest application itself was successful and brought the tool one step closer to a full implementation. However, as with any newly proposed method, it needs more testing, and in order to be able to use it in the future, we make a series of recommendations for future applications.

1. Introduction

Probabilistic models for long-term (years) volcanic hazard assessment and short-term (hours to few days) eruption forecasting have been of increasing interest in the past two decades for volcanologists, civil authorities, and stakeholders alike. Although traditional deterministic hazard forecasting based on the eruptive history of the volcano has proven useful throughout the years for volcanoes that erupt frequently and have a well-preserved geological record [e.g., *Crandell et al.*, 1984; *Haynes et al.*, 2007; *Parfitt and Wilson*, 2008], a more quantitative probabilistic method could add value to any deterministic approach for long-quiescent volcanoes, given the high complexity and randomness of volcanic processes and given our partial understanding of such processes [e.g., *Selva et al.*, 2012; *Lindsay et al.*, 2010]. At volcanoes with many recorded eruptions, a simple statistical analysis of the time series of eruptions may help forecast the next event [e.g., *Bebbingtom*, 2013; *Furlan*, 2010; *Connor et al.*, 2006; *Decker*, 1986] and commonly will result in a calculation of the recurrence time of a specific type of eruption [e.g., *Thouret et al.*, 1999a; *Lindsay et al.*, 2005b]. Even so, volcanoes are intrinsically highly uncertain systems [e.g., *Marzocchi and Bebbington*, 2012]. The further we go back in time (e.g., > 10,000 years) the less complete the geological record may be, due to erosion and covering by more recent deposits, thus our interpretation will be biased toward larger magnitude events [e.g., *Brown et al.*, 2014; *Sandri et al.*, 2014; *Crosweller et al.*, 2012]. Long repose intervals along with changes in eruptive behavior and volcano morphology are a further source of uncertainty in long-term hazard assessment [e.g., *Decker*, 1986; *Scott*, 1984].

Short-term eruption forecasting is also challenging. Volcanoes can undergo phases of "*unrest*" [e.g., *Marzocchi et al.*, 2004; *Marzocchi and Bebbington*, 2012] that can last from several hours to several years [e.g.,

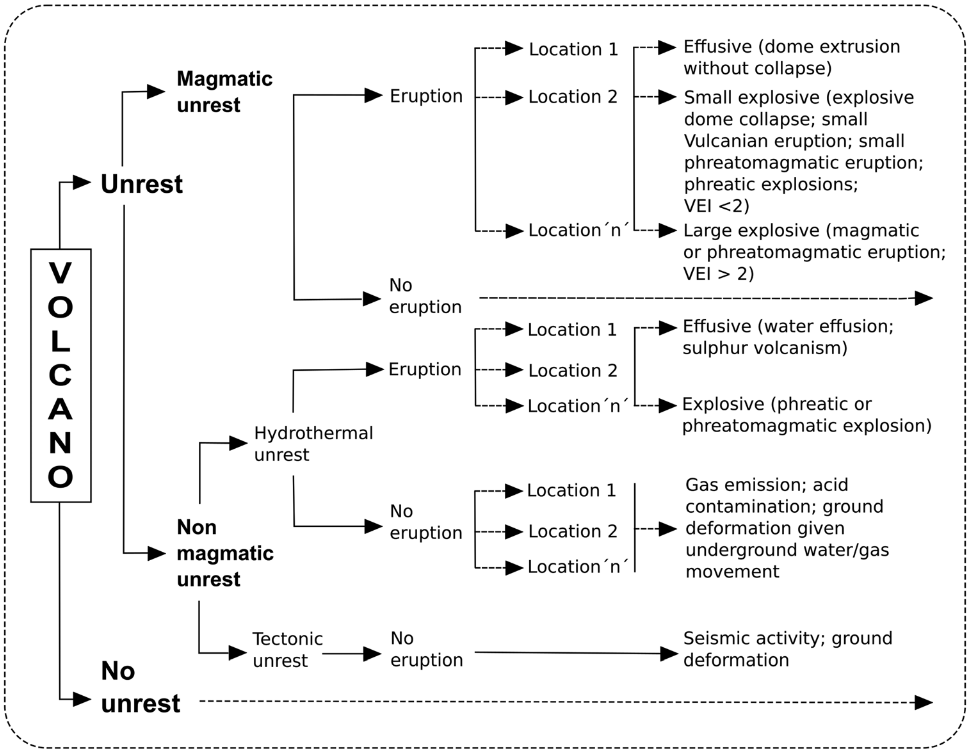

Figure 1. Graphic representation of the BET_UNREST event tree adopted for southern Dominica during the VUELCO Simulation Exercise. The Event Tree was developed for three kinds of volcanic unrest—magmatic, hydrothermal, and tectonic—with the expected outcomes. Note that under "magmatic branch" we also consider the occurrence of (a) small phreatic/phreatomagmatic explosions for "*small explosive type*" and (b) magmatic/phreatomagmatic for "*large explosive type*." The "*explosive type*" outcome of hydrothermal unrest may also lead to "phreatomagmatic explosions" (see text).

Phillipson et al., 2013]. During such unrest phases, a series of geophysical, geochemical, and geodetic signals are observed that may be precursory to an eruption, or just a manifestation of a reactivated system that will subside after a period of time. Oftentimes, during such unrest periods, volcanologists are asked to provide advice to inform mitigation measures such as evacuation [e.g., *Marzocchi and Bebbington*, 2012]. If the unrest culminates in an eruption, such actions are deemed successful (e.g., the evacuations before the recent eruptions of Villarrica and Calbuco in early 2015) [*Global Volcanism Program*, 2015a, 2015b]. The situation is more challenging, however, when unrest does not culminate in an eruption, as people may perceive that the mitigation measures, particularly when associated with economic losses, were not justified by the outcome of the unrest [*Phillipson et al*., 2013] (examples are Campi Flegrei in 1980 [*Barberi et al*., 1984]; Guadeloupe in 1976 [*Fiske*, 1984]). Still, many will claim the actions were valid, and that given the high stakes involved, society must be willing to live with such false alarms [*Marzocchi and Woo*, 2007, 2009]. In any case, the better we understand the characteristics of previous unrest phases and their outcomes, the better we can quantify, in a timely manner, the likelihood of particular outcomes of unrest in the future [*Potter et al*., 2015a, 2015b]. The complexity of precursory signals and the possibility that such precursory phenomena may not lead to an eruption makes a probabilistic approach for eruption forecasting appealing [e.g., *Marzocchi et al*., 2004, 2008, 2010; *Marzocchi and Bebbington*, 2012; *Selva et al*., 2012; *Brancato et al*., 2011].

A common probabilistic approach for eruption forecasting and volcanic hazard assessment is the use of probabilistic event trees [e.g., *Newhall and Hoblitt*, 2002; *Marzocchi et al*., 2004, 2008, 2010; *Neri et al*., 2008; *Marti et al*., 2008]. This approach can be applied to volcanoes with or without well-known eruption records, and with or without past monitored eruptions [*Marzocchi and Bebbington*, 2012]. An event tree structure is a graphic representation of events in which branches are logical steps from a general prior event (e.g., initiation of unrest) through subsequent events (e.g., origin of unrest) to final outcomes (e.g., eruption; occurrence of a certain volcanic phenomena) (Figure 1). This method has been adopted with a Bayesian framework by *Marzocchi et al*. [2008, 2010] and adapted as a computer code that can be used as a near real-time computational tool with the potential to be used in decision making during volcanic crises [e.g., *Lindsay et al*., 2010]. Hereafter we will refer to this methodological framework with the acronym BET (Bayesian Event Tree).

Previous applications of the BET model for Eruption Forecasting (BET_EF) have been carried out retrospectively for unrest periods that have or have not led to an eruption (e.g., Etna [*Brancato et al*., 2011]; Morne aux Diables [*Constantinescu et al*., 2014]) and during volcanic crisis simulation exercises conducted by civil authorities (e.g., for Vesuvius during the MESIMEX exercise [*Marzocchi et al*., 2008]; for the Auckland Volcanic Field during Exercise Ruaumoko [*Lindsay et al*., 2010; *Constantinescu and Lindsay*, 2010]; and for Cotopaxi during a VUELCO Simulation Exercise [*Constantinescu et al*., 2015, *Sandri et al*., 2016]). This model is limited to computing probabilities related to a volcanic crisis of magmatic origin and its subsequent possible outcomes (i.e., magmatic eruption). However, there are numerous examples in recent history where possibly nonmagmatic unrest has had significant social and economic impacts (e.g., Soufrière, Guadeloupe 1976 [*Fiske*, 1984]; Campi Flegrei, Italy 1980 [*Barberi et al*., 1984; *Dvorak and Mastrolorenzo*, 1991]). In a recent review of nonmagmatic unrest, *Rouwet et al*. [2014] identified potential hazards related to hydrothermal and tectonic unrest (e.g., phreatic explosions, acid contamination, and gas emissions). The challenge is in identifying the precursory signals that allow determination of the monitoring parameters and thresholds that can differentiate between the types of unrest. Given the importance and potential impacts of unrest of different origins (e.g., hydrothermal; tectonic), in the framework of the European Commission VUELCO (EC-FP 7, Volcanic Unrest in Europe and Latin America) project, the BET_EF model was extended to include unrest of nonmagmatic origin and its subsequent possible outcomes. The new model, called BET_UNREST (Bayesian Event Tree for Volcanic Unrest) is based on the same event tree methodology as BET_EF, the only difference being the fact that at the "no-magma" node, "hydrothermal" and "tectonic" branches along with their potential hazards have been added [*Tonini et al*., 2016; *Sandri et al*., 2016; *Rouwet et al*., 2014] (Figure 1).

In this paper, we describe the application of the newly created software implementation of the BET_UNREST model, called PyBetUnrest (https://vhub.org/resources/betunrest) during the VUELCO Simulation Exercise carried out on the island of Dominica, Lesser Antilles, in May 2015. This simulation exercise provided an excellent opportunity to test the integration of probabilities obtained by BET_UNREST into the decision-making process. We tested the tool in real time by observing how it performed, and how its results were interpreted and used by the Scientific Team. Our objective was twofold: (i) to test PyBET_UNREST by identifying how our assumptions for input data affected the calculated probabilities and (ii) to observe how the obtained probabilities were perceived by the Scientific Team and to what extent they were considered in the deliberations. In the following sections, we describe the context and setup of the simulation exercise, the setup of BET_UNREST and the results obtained using the PyBetUnrest tool. We then discuss the results in the context of lessons learnt and make suggestions for future applications.

2. Dominica Volcanism and Hazard Management

Dominica lies in the Lesser Antilles volcanic arc and has one of the highest concentrations of potentially active volcanoes in the world, with nine volcanic centers within an area of 750 km^2 (Figure 2). Its last magmatic eruption was as recent as $\sim$500 years ago [*Lindsay et al*., 2005a, 2005b]. The oldest volcanic centers are found in eastern Dominica, where activity dates back to 6.8–5.2 Ma [*Howe et al*., 2015a; *Smith et al*., 2013; *Lindsay et al*., 2005b]. The initiation of more evolved volcanism started in northern Dominica in the Pliocene ($\sim$3.7–1.8 Ma) [*Howe et al*., 2015a; *Smith et al*., 2013]. Morne Diablotins (1421 m asl) in the north is a large andesitic stratovolcano characterized by Pelean-type activity alternating with Plinian eruptions (Figure 2).

Morne aux Diables (856 m asl), the northernmost volcanic center (Figure 2), consists of a central stratocone bordered on its southern flanks by five parasitic domes. Activity is characterized by Pelean dome growth and collapse, but ignimbrites and pumice-surge deposits suggest that Plinian-type eruptions have also occurred. Although there is no historical eruption documented for these two centers, the frequent seismic swarms and geothermal activity in the area suggest they may be potentially active [*Lindsay et al*., 2005b].

Southern Dominica (south of latitude 15°25′N) represents an intriguing volcanic environment. Volcanic activity in Dominica is believed to have migrated to the southern half of the island around 1 Ma ago [*Lindsay et al*., 2005a, 2005b; *Howe et al*., 2015b]. Six volcanic centers are clustered in an area of 24 $\times$ 22 km (Figure 2). Typically, the volcanic centers in the south (e.g., Plat Pays Volcanic Centre (PPVC), Trois Pitons,

Figure 2. Shaded relief map of Dominica, W.I. (UTM 20 N), showing the distribution of the nine volcanic centers. The highlighted box caption around the southern part of the island indicates the area of the most recent activity in Dominica and the area on which the probabilistic assessment was conducted using BET_UNREST (adapted from The University of the West Indies, Seismic Research Centre (unpublished data, 2005)).

Micotrin, Grand Soufrière Hills, Morne Watt, Morne Anglais) consist of a central dome surrounded by parasitic domes and associated block-and-ash-flow and pumiceous pyroclastic flow deposits [*Lindsay et al*., 2003; *Howe et al*., 2015b; *Smith et al*., 2013]. Volcanism in this region has been predominantly Pelean-style dome-forming eruptions but widespread ignimbrites thought to be sourced from the Wotten Waven/Micotrin area suggest that Plinian eruptions have also occurred [*Lindsay et al*., 2005b; *Smith et al*., 2013; *Howe et al*., 2014]. In the last 60 years since monitoring started, seismicity and geothermal activity have occurred diffusely beneath the region. Frequent volcanic earthquake swarms at shallow depths over the past 20 years [*Lindsay et al*., 2003; *Watts et al*., 2010], together with intense geothermal activity (especially associated with the PPVC, Valley of Desolation (VoD)/Boiling Lake (BL) and Watten Waven/Micotrin centers) and recent phreatic explosions (1997) indicate the region is still active, necessitating close monitoring and effective volcanic hazard assessment and management. Phreatic explosions originating from the Valley of Desolation area occurred in 1880 and 1997 and the most recent magmatic activity occurred from a dome in the Plat Pays Volcanic Center (PPVC). The products of the phreatic explosion on 8–9 July 1997 contained fragments of nonaltered lava, rounded hydrothermally altered igneous minerals and hydrothermal minerals such as silica and iron oxides. The event was a small phreatic eruption, most likely triggered by reactivation of the hot springs area in the preceding months together with the occurrence of several landslides from the unstable walls of the Valley of Desolation [*Lindsay et al*., 2005b; J.-C. Komorowski and G. Hammouya, Analytical results and report on the current activity of the Soufrière area as of December 8–9, 1998, unpublished report, 1998].

In a hazard assessment of the island, *Lindsay et al*. [2005b] present six possible eruptive scenarios, most of which are focused in the southern half of the island reflecting the most recent activity. The most likely scenario was considered to be a phreatic explosion in the Boiling Lake/Valley of Desolation area, similar to the 1997 event. The most likely magmatic activity was thought to take the form of Montserrat-style dome-forming eruptions in the Plat Pays, Watten Waven/Micotrin and Morne aux Diables areas. Given the evidence for past Plinian eruptions, the worst-case scenario was considered to be an explosive eruption from the Watten Waven/Micotrin center, the region thought to have been the source of the largest Plinian eruptions in the past [*Lindsay et al*., 2005b]. Hazard maps generated for these scenarios were combined into a map of integrated hazard zones for Dominica. We refer to *Lindsay et al*. [2005b] for a thorough description of the selected scenarios and the integrated hazard map.

The UWI Seismic Research Center (SRC) is the agency responsible for volcano monitoring in Dominica and for providing scientific advice to authorities during a crisis. Monitoring started in 1953 with a single seismograph and has been progressively upgraded over the years, with the current network consisting of: 12 permanent seismic stations (9 short period and 3 broadband), 22 GPS benchmarks used for periodic GPS campaigns, 3 continuous GPS stations, and gas and fluid sampling in geothermal areas every 2 years. An Alert Level System is used to manage periods of unrest at volcanoes in Dominica. The system, which consists of four color-coded levels, is used to inform local authorities of the level of activity at volcanic centers with recommended actions to be taken to mitigate potential impact (SRC, http://www.uwiseismic.com/General.aspx?id=54).

The Office of Disaster Management (ODM) of the Ministry of National Security, Immigration and Labour is the agency responsible for civil defense and emergency management related to all hazards in the Commonwealth of Dominica. The National Volcanic Contingency Plan guides actions in the event of a volcanic crisis; its objectives are to prevent loss of life, to safely relocate the population, to inform and direct relevant agencies and to educate the public. More regionally, the Regional Response Mechanism (RRM) guides the regional response and facilitates collaboration and cooperation between the Caribbean Disaster Emergency Management Agency (CDEMA) and a number of key regional organizations that are mobilized in the event of a national emergency in Dominica. It is based on a collection of Agreements, Memoranda of Understanding and Protocols for the provision of assistance to CDEMA Participating States (CDEMA-PS) impacted by events.

3. The VUELCO Simulation Exercise

A VUELCO Volcanic Unrest Simulation Exercise was held in Dominica on 14–15 May 2015. The main objectives of the exercise were to test, through a simulated unrest episode in South Dominica: (1) the communication of scientific information from the monitoring scientists to the ODM; (2) the ODM response mechanism for volcanic emergencies; (3) the emergency protocols of the SRC and RRM; and (4) the feasibility of applying probabilistic models for volcanic hazard assessment developed within the framework of the VUELCO project (e.g., BET_UNREST) during a volcanic emergency.

During the Exercise, members of the involved agencies were divided into five teams with specific tasks: (1) the "Volcano Team," comprising the scientists who developed the scenario; this team was tasked with

Table 1. Summary of the Volcanological Data Provided in the Scientific Inject Bulletins for Each Phase of the Simulation Exercise

Simulated Phase	Summary of the Volcanological Data
Phase I	
Seismology	S Dominica: Number of VTs increase from 25 in July through 108 in August 2014 to 356 in October 2015; quiescence in December; from January the activity increased constantly reaching up to 580 events in March 2015.
Deformation	GPS measurements showed small vertical deformation (order of mm) compared to background, and a northward movement in the area of Boiling Lake/Valley of Desolation/Soufriere.
Geochemistry	Slight changes in the acidity of springs around Boiling Lake/Valley of Desolation and Sulphur Springs areas.
Other observations	Visual observations of landslides and new areas of venting in Boiling Lake/Valley of Desolation.
	New areas of venting in Sulphur Springs area.
Phase II	
Seismology	In May 2015 there were over 1000 VTs and 5 hybrid events recorded, mostly clustered below the Boiling Lake and Trois Pitons areas; seismicity decreased from June to September when a regional tectonic earthquake occurred; seismicity pattern changes in November with hybrid events becoming predominant and number of VTs decreasing to ~80 events.
Deformation	GPS measurements revealed an uplift of ~5 cm in the Boiling Lake/Valley of Desolation area.
Geochemistry	T^0 and acidity of waters returned to the normal background levels for the hydrothermal system of Dominica; drainage of Boiling Lake occurred in May 2015 but it refilled in September 2015; HCl levels slightly elevated.
Other observations	An ash eruption occurred in the Boiling Lake area in November 2015; the erupted material is hydrothermally altered but 1–5 vol % is believed to be fresh glass.
Phase III	
Seismology	From December 2015, VT activity dropped back completely with pulsing swarms of hybrid earthquakes dominating the activity. The events are being recorded on a single station located in the Valley of Desolation. From January to March, the numbers averaged around 200. From April, the numbers of hybrids reduced steadily down to zero in July.
Deformation	Starting mid-June, data show subsidence of 2.5 cm; inflation resumes in mid-July and a new source of deformation is indicated.
Geochemistry	T^0 and acidity of waters remained at background level for the hydrothermal system of Dominica; HCl levels dropped to background.
Other observations	Sulphur fires in March 2016 in the Soufriere region; 17 June 2016, a scientist at an institution overseas concluded from satellite imagery that an eruption is imminent in Valley of Desolation area.

providing exercise injects informing on the state of activity at the volcano; (2) the "Scientific Team," comprising the scientists of the VUELCO consortium and SRC; this team divided itself into four groups tasked with interpretation of geochemical, seismic, and geodetic data, with one "BET Group" tasked with running the probabilistic model BET_UNREST to determine probabilities of (i) unrest, (ii) origin of unrest, and (iii) eruption of whatever nature. The Scientific Team (excluding the BET Group) was also tasked with providing scientific bulletins to the ODM. (3) The "ODM Team" comprising local disaster management officials; (4) the "CDEMA Team" consisting of members of the RRM; and (5) the "Evaluators/Observers Team," which was tasked with the evaluation of the exercise and its effectiveness. We note that the authors of this paper belonged to either the "Volcano Team" or the "BET Group," i.e., were not directly involved in the scientific deliberations and interaction with the ODM.

The Dominica VUELCO scenario was developed in secret by scientists drawn from SRC, Montserrat Volcanic Observatory and the University of Auckland (New Zealand). The "Volcano Team" did not participate in the discussions and deliberations conducted by the Scientific Team during the exercise. The simulated unrest activity was provided to the Scientific Team in three "phases" through exercise injects comprising processed data (i.e., seismic, geochemical, deformation, and visual observations) derived from the monitoring network. A summary of the activity reported in the three phases is given in Table 1. The scenario was based on a possible eruption somewhere in Southern Dominica. It covered a period of unrest activity of 2 years from July 2014 until July 2016, starting with an increase in seismicity in Southern Dominica in August 2014 accompanied by changes in the acidity of the waters in Valley of Desolation and Sulphur Springs areas (Phase I; Table 1). The scenario continued with a state of increased activity around the Boiling Lake/Valley of Desolation accompanied by an ash explosion (Phase II; Table 1), and concluded with a general return to background levels in some parameters (e.g., geothermal) although seismicity remained somewhat elevated (Phase III; Table 1). After each phase, the Scientific Team presented a report to the ODM with their prognosis of the situation and some recommendations in terms of mitigation actions that may be considered within the context of the Alert Level System (e.g., changes in alert level). Unlike previous applications where BET models were run separately from the exercise in order for the results to be compared with Scientific Team output, in Dominica, the model was actually applied in real time by the "BET Group" and the results obtained were taken into consideration during discussions by the Scientific Team, making this the first exercise in which results from a probabilistic model have been considered in such deliberations.

4. Setting Up BET_UNREST for Southern Dominica

Following the same scheme as other BET models, BET_UNREST uses past data, prior models and monitoring information at each computational node to provide probabilities of the outcomes of a magmatic, hydrothermal, or tectonic unrest. A thorough description of BET_UNREST and the software implementation PyBetUnrest used in this exercise can be found in *Tonini et al*. [2016]. In Figure 1, we illustrate the structure of the BET_UNREST event tree adopted for Dominica.

The setup of BET_UNREST model should follow two keystone "rules": (1) past data and prior models at each node should be an accurate and consistent representation (i.e., to our best knowledge) of the volcano's eruptive history and behavior and (2) monitoring parameters for each node should be designed in such a way as to detect any "anomaly" with respect to the background activity. The definition of what is background versus anomaly and the interpretation of anomalies is of primary importance. Basically, it allows the interpretation and quantification of anomalies in the evolving monitoring information at each node and provides the probability of an event occurring in the next time window $[t_{0,}\ t_0+\tau]$, where t_0 is the present time and τ is the length of the time window considered (e.g., 1 month) [*Marzocchi et al*., 2008]. When anomalies are detected (i.e., through new monitoring information) BET_UNREST estimates the probabilities of having unrest of a specific origin—magmatic, hydrothermal, and tectonic—that may/may not lead to an eruption in the given time window. When no monitoring information is used in the calculation (i.e., no anomaly is detected) BET_UNREST relies on background information (past data and prior models) and provides long-term probabilities [see *Tonini et al*., 2016].

Before the exercise we conducted five discussion-based elicitation sessions with a panel of experts in (a) volcano monitoring of Dominica (personnel from SRC) and (b) use of PyBetUnrest (personnel from INGV, Italy), in order to establish the monitoring parameters and their related thresholds. Importantly, SRC members that participated in the elicitation sessions were also members of the Scientific Team during the Simulation Exercise. A complete list of experts involved in the BET_UNREST setup for the Dominica exercise is provided in the endnotes. During the elicitation process, each expert was asked to provide a list of parameters, thresholds, inertia [see *Selva et al*., 2012] and weights (i.e., a measure of importance of the parameter) [*Marzocchi et al*., 2008]. The used thresholds can be either Boolean (i.e., yes/no; BET notation [=1]) or Fuzzy, representing a gradual increase of the anomaly of a parameter (i.e., a lower and upper value indicating a state from "less anomalous" to "highly anomalous"). We refer the reader to *Marzocchi et al*. [2008] and the associated Electronic Supplement Material for a more in-depth description. The concept of "inertia" in BET parameters has been introduced to define the length of time an anomaly remains significant for forecasting purposes [*Selva et al*., 2012]. The number of parameters, their definition and their values varied throughout each elicitation session, and the panel of experts only reached a consensus at the last meeting. At the end of the elicitations, the experts defined to the best of their knowledge the background activity in Southern Dominica, and which parameters they expect to show anomalies, should unrest occur. Given the fact that in Dominica unrest may be triggered by magma, the hydrothermal system or tectonic events, monitoring parameters were specifically designed in order to reveal anomalies related to each type of manifestation of unrest. Monitoring parameters are mostly Boolean (i.e., we either see or do not see a change in a parameter) in order to accommodate the relative modest monitoring network of Dominica. In the following section we provide a description of the philosophy adopted in setting up the BET_UNREST for Dominica (BET_UR_DOM) and note that the code is "open" to updates in the future as new information becomes available. The input data for each node are summarized in Tables 2a and 2b. We refer the reader to Figure 1 for the names of the various nodes.

4.1. Unrest/No Unrest

In order to estimate the probability of unrest (of any origin) in the next time interval $t_{0,}\ t_0+\tau$ (1 month in this application), we have to define the *past data*, *prior models*, and *monitoring parameters* pertinent to "detection" of unrest. We consider that unrest may be of purely magmatic origin (i.e., magma directly identified as the cause of the unrest episode; magma-on-the-move) or of other causes, like hydrothermal (i.e., strictly caused by the hydrothermal system) or tectonic.

For *past data*, we calculated the number of unrest episodes (of any origin) since monitoring started in Dominica in 1953 up until April 2014. Unrest was defined by the expert panel as the period for which the number of VTs (volcano-tectonic earthquakes) exceeded 10 events per day for at least 2 weeks. The phreatic

Table 2a. Summary of the Input Data for the Magmatic Branch of BET_UR_DOM[a]

Input Parameter	Data/Thresholds/Inertia
NODE 1: UNREST	
Nonmonitoring Component	
Past data	$n_1 = 615$; $u = 14$
Prior models	$\Theta = 0.5$; $\Lambda = 1$ (uniform. dist.; see text)
Monitoring Component	
1. Increase in T^0 of hot springs and/or fumaroles	=1[b]
2. Increased CO_2 flux above background	=1
3. Change in H_2O/CO_2	=1
4. Appearance of new fumaroles and/or hot springs	=1
5. Vegetation die back	=1
6. Any LPs or hybrids	=1
7. Large regional tectonic event	=1 [magnitude > 7, Caribbean Region][c]
8. Number of VTs	>10 day^{-1} [consistent for 2 weeks]
9. Detectable ground deformation	=1 [coherent signal above background]
NODE 2: MAGMATIC UNREST	
Nonmonitoring Component	
Past data	$m_u = 13$
Prior models	$\Theta = 0.5$; $\Lambda = 1$ (uniform. dist.; see text)
Monitoring Component	
1. Increase in C/S, or decrease after increase	=1 [daily to weekly]
2. Detectable SO_2, HCl, HF	=1 [daily to weekly]
3. Extreme increase in T^0	=1 [> 300°C]
4. Any VLPs	=1
5. Number of LPs after significant VTs swarm	>5, 10 day^{-1} [week]
6. Consistent increase in no. of VTs for 1 month	=1 [month]
7. Deep VTs	>4, 5 $week^{-1}$ [>8 km]
8. Detectable radial deformation [localized]	=1 [coherent signal above background]
9. Surface deformation [island wide]	>2, 2.1 cm [in more than 6 months]
NODE 3: MAGMATIC ERUPTION	
Nonmonitoring Component	
Past data	No data
Prior models	$\Theta = 0.64$, $\Lambda = 1$ [*Phillipson et al.*, 2013, see text)
Monitoring Component	
1. Decreasing C/S after increase	=1
2. Increase in Cl, Br, F content in hot springs/pools	=1
3. Decrease in H_2O/CO_2 and/or H_2S/SO_2 and/or SO_2/HCl	=1
4. Phreatic activity	=1
5. Large thermal anomaly [incandescence]	=1
6. Landslides in hydrothermal areas	=1
7. Acceleration of VTs, LPs, hybrids	=1 [weekly]
8. Presence of harmonic tremor	=1
9. Shallowing of VTs hypocenters in the edifice	=1 [<3 km]
10. Sudden reversal of activity	=1
NODE 4: VENT LOCATION	
Nonmonitoring Component	Grid map of 22 × 24 km; cell size 1 × 1 km
Past data	Uniform distribution across volcanic centers (17 cells)
Prior models	Uniform distribution for cells falling on land and 0 for cells falling offshore (see text)
NODE 5: ERUPTION SIZE/STYLE	
Nonmonitoring Component	3 scenarios: (1) effusive (Ef); (2) small explosive (SE); (3) large explosive (LE)
Past data	Ef: 0 events; SE: 5 events; LE: 2 events
Prior models	Ef/SE/LE = 0.83/0.14/0.03 (see text)

[a]Monitoring parameters as well as past data and prior models are given with their respective thresholds and units.
[b]Boolean parameter threshold (yes/no).
[c]Between square brackets is the "inertia" of the parameter (see text); n_1 total length of the data catalogue considered; u total number of unrest episodes; and m_u total number of magmatic unrest episode.

explosion of 1997 was also counted as an unrest episode. Based on this definition, we obtained 14 unrest episodes covering a total of 126 months. Since no reliable information was available for *prior models*, we used a so-called maximum ignorance distribution, i.e., beta distribution mean equal to 0.5 (both outcomes have equal likelihoods to occur) and equivalent number of data Λ equal to 1 (indicating the fact that we have a large uncertainty; see *Marzocchi et al*. [2008, Appendix B and Figure 4]).

Table 2b. Summary of the Input Data for the Hydrothermal Branch of BET_UR_DOM[a]

Input Parameter	Data/Thresholds/Inertia
NODE 1: UNREST	Same as magmatic branch[b]
NODE 2: HYDROTHERMAL UNREST	
Nonmonitoring Component	
Past data	$h_u = 1$ (see text)
Prior models	$\Theta = 0.5$; $\Lambda = 1$ (uniform. dist.; see text)
Monitoring Component	
1. Anomalous behavior of BL [overflow, lower or higher T than usual, no return of lake, etc.]	=1
2. Changes in hydrothermal features	=1
3. Increase in B and/or NH_4 concentration in waters	=1
4. Increase in CH_4/CO_2 (fumaroles)	=1
5. Increase in T^0 of fumaroles	>5, 10 day^{-1} [week]
NODE 3: HYDROTHERMAL ERUPTION	
Nonmonitoring Component	
Past data	1 (see text)
Prior models	$\Theta = 0.5$; $\Lambda = 1$ (uniform. dist.; see text)
Monitoring Component	
1. Increase in T^0 of fumaroles	$>120^{\circ}$, 200^0
2. Rise of water level in pools/overflow of BL	=1
3. Increasing in extension of fumarolic field	=1
4. Muddy pools	=1
5. Boiling/bubbling of pools that previously did not	=1
6. Inflation of fumarolic field	=1
7. Landslides in hydrothermal areas	=1
8. New/extension of alteration areas	=1
NODE 4: VENT LOCATION	Same as magmatic branch
NODE 5: ERUPTION SIZE/STYLE	
Nonmonitoring Component	2 scenarios: (1) explosive eruption (Ex); (2) effusive eruption (Ef)
Past data	Ex/Ef = 1/0
Prior models	Ex/Ef = 0.7/0.3 (see text)

[a]Monitoring parameters as well as past data and prior models are given with their respective thresholds and units.
[b]Nodes 1 and 4 are common to both hydrothermal and magmatic branches of the Event Tree; h_u = total number of magmatic unrest episodes.

For the *monitoring component*, we defined nine parameters (five geochemical, three geophysical, and one geodetic; see Table 2a for their thresholds and inertia).

4.2. Origin of Unrest: Magmatic

Given the detection of unrest in the previous node, we want to compute the probability that this unrest is of magmatic origin. For *past data*, we consider 13 of the 14 previously identified unrest episodes as having magmatic origin (i.e., the VT swarms were acknowledged by monitoring experts as being due to magma-on-the-move; the phreatic eruption was not). As *prior models*, we used a maximum ignorance distribution.

The *monitoring component* consists of three geochemical, four geophysical, and two geodetic parameters (Table 2a).

4.2.1. Eruption/No Eruption

The probability of having an eruption given detection of magma migration at the previous node is computed. No past magmatic unrest episode led to an eruption therefore no *past data* were used at this node. For *prior models*, we relied on the *Phillipson et al*. [2013] unrest catalogue, according to which 64% of magmatic unrest at complex volcanoes resulted in an eruption; therefore we used a prior mean equal to 0.64 and $\Lambda = 1$. Although this does seem high given the ratio based on the very recent history of Dominica—it does represent the most recent compilation of unrest data, therefore we chose to use this as our prior for this node.

We used 10 monitoring parameters at this node, summarized in Table 2a.

4.2.2. Magmatic Vent Location

The fact that past seismic swarms on Dominica are not clearly associated with a particular center, together with the proximity of the volcanic centers to each other, and the intercalated nature of stratigraphic sequences, we choose to consider Southern Dominica as a single volcanic complex (similar to a volcanic field) in our probabilistic framework; an attempt to assess each volcanic center on its own would be almost impossible.

In BET_UNREST, we treat Southern Dominica like a volcanic field, defining a grid of 24 $\times$ 22 km with cell size of 1 km. As *past data*, we use the past volcanic centers (that are hosted by 17 grid cells). For *prior models*, we use a uniform distribution over the cells that fall on the mainland, as expert elicitation assumed that no eruption would occur offshore.

For the *monitoring component*, we try to localize all the anomalies (if any) of the parameters defined at the previous nodes in order to assess the probability of a future vent opening.

4.2.3. Magmatic Eruption Size/Type

Considering the past magmatic activity in the area and the most likely scenarios of *Lindsay et al*. [2005b], we defined three possible types of magmatic (or phreatomagmatic) eruption, independent of vent position: (1) *effusive* (*dome extrusion*, *without collapse*); (2) *small explosive* (*VEI* ≤ 2) (*e.g., explosive dome collapse*; *small Vulcanian eruption*; *small phreatomagmatic eruption*; *phreatic explosions*); and (3) *large explosive* (*e.g., magmatic or phreatomagmatic eruption* (*VEI* > 2)). For *past data*, we used information on eruption types over the last 10,000 years. Despite having information on older events, we assumed that the further we go back in time, the more bias we may add to the calculation by not accounting for events we are yet to identify (i.e., incomplete record). We obtained 0 *type 1* events, 5 *type 2* events, and 2 *type 3* events. As *prior models*, we rely on a power law derived from the *Simkin and Siebert* [1994] catalogue according to which the mean probabilities are 0.83, 0.14, and 0.03, respectively, for types 1, 2, and 3.

Given the modest monitoring network in Dominica, we also assume that *monitoring parameters* seldom offer insights into the size and style of an impending eruption [*Brancato et al*., 2011; *Sandri et al*., 2004].

Since the purpose of the exercise was tracking the evolution of unrest and forecasting a possible eruption, we did not define the further nodes, as they are related to the impact of a potential eruption on the surroundings of the volcano.

4.3. Origin of Unrest: Hydrothermal

Given the detection of unrest, we want to compute the probability of this unrest being a manifestation of the hydrothermal system. For *past data*, we have one hydrothermal unrest episode (i.e., the 1997 Valley of Desolation phreatic explosion). For *prior models*, we use again a maximum ignorance distribution.

Five *monitoring parameters* were defined in order to detect hydrothermal unrest (Table 2b).

4.3.1. Hydrothermal Eruption/No Eruption

For *past data*, we count one eruption out of one hydrothermal unrest episode (i.e., the 1997 phreatic explosion in VoD). As *prior models*, we use again a maximum ignorance distribution since we could not find a more reliable model.

The *monitoring component* comprises eight parameters summarized in Table 2b.

4.3.2. Hydrothermal Vent Location

For the hydrothermal branch of the event tree, we use the same vent location distribution as defined in the magmatic branch. As regards to the *monitoring component*, we localize the anomalies, if any, at the nodes leading to this branch (similar to the magmatic vent distribution).

4.3.3. Hydrothermal Eruption Type/Size

The outcome of a hydrothermal unrest eruption was assumed to be either *effusive* (e.g., water effusion) or *explosive* (e.g., phreatic explosion and small phreatomagmatic (i.e., a small phreatic explosion might suddenly decompress the underlying magma at rest)) (Figure 1). As *past data*, we have 1 explosive and 0 effusive events. For *prior models*, we assume a subjective choice in which the prior means are 0.3 and 0.7, and $\Lambda = 1$, respectively for the *effusive* (e.g., water effusions) and *explosive* type (e.g., phreatic; small phreatomagmatic) (based on a relatively more frequent explosive activity observed at other hydrothermal systems such as e.g., Poás, Costa Rica [*Rouwet et al*., 2016b; *de Moor et al*., 2016] and Turrialba, Costa Rica [*Conde et al*., 2014]).

5. Results

Assuming the input data were correct to the best knowledge of the experts involved in volcano monitoring who populated the code, BET_UNREST enables us to estimate in near real time the probabilities of having

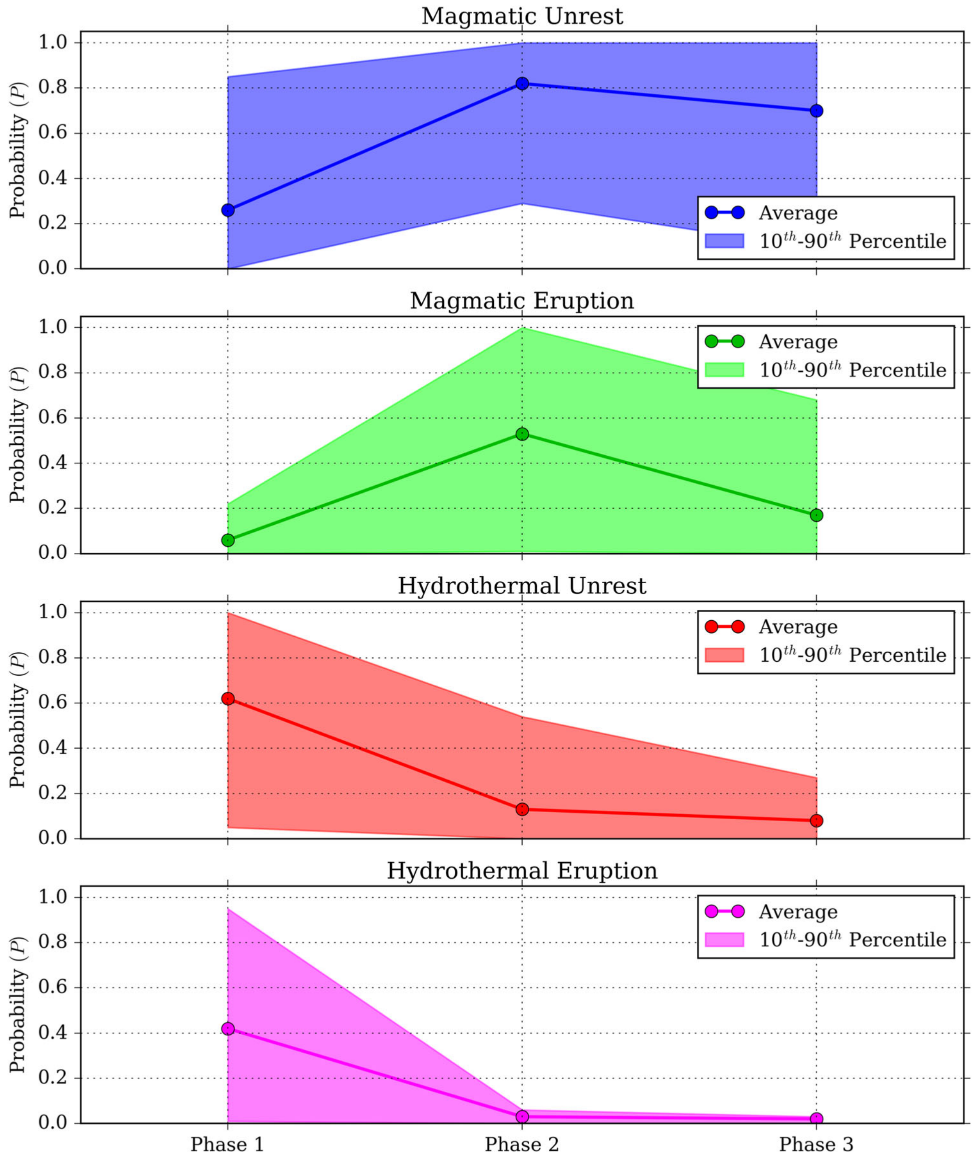

Figure 3. Time evolution of the absolute monthly probabilities and associated uncertainty produced by BET_UNREST according to each of the three phases of the simulation exercise. During Phase I, the probabilities of hydrothermal unrest and hydrothermal eruption were higher than those of magmatic branch because most anomalies observed at Node 2 were considered strong indicators of hydrothermal activity and at Node 3 magmatic branch there was no anomaly recorded. For Phase II report, the magmatic unrest and magmatic eruption probabilities increased significantly mostly due to the fact that "phreatic activity" parameter was considered as a strong precursor to magmatic eruption. Probabilities obtained for Phase III reflect the overall pattern of decreasing activity. Throughout the three phases, the uncertainties related to the probabilities obtained could not have been reduced without strong corroboration between monitoring signals.

(i) *unrest* of (ii) magmatic, hydrothermal, or tectonic *origin*, which may or may not lead to an (iii) *eruption* in a predefined (iv) *location* and that the eruption will have a selected (v) *size*. By using past data and prior models, BET_UNREST provides the background probability estimates for the next time window. However, if anomalous activity is detected, the information is updated via monitoring parameters and thus BET_UNREST allows us to incorporate the changes in the flux of monitoring data in the estimation of probabilities for the next time window.

In this section, we present the probability estimates obtained by BET_UNREST according to the monitoring information provided in each of the three exercise injects (i.e., from each of the three phases) during the VUELCO Simulation Exercise in Dominica (Table 3, Figure 3). In particular, we report on the data provided in all phases of the exercise and the pertinent information used as input in BET_UNREST.

Table 3. Summary of the Anomalies Detected in the Parameters for Each Computational Node of BET_UNREST and the Probabilities Obtained for Each Phase of the Simulation Exercise

Phase	Anomalies Detected in Monitoring Parameters	Probabilities Obtained
Phase I		
Node 1	Increase in T of thermal springs and fumaroles	$P_{unrest} = 100\%$
	Landslides in hydrothermal areas	
	Appearance of new fumaroles	
	Appearance of hybrid and/or LP earthquakes	
Node 2	*Magmatic unrest*: NO anomalies detected	$P_{magmatic\ unrest} = 26\%$
	Hydrothermal unrest: changes in hydrothermal features	$P_{hydrothermal\ unrest} = 62\%$
	Landslides in hydrothermal areas	$P_{tectonic\ unrest} = 12\%$
Node 3	*Magmatic eruption*: NO anomalies detected	$P_{magmatic\ eruption} = 6\%$
	Hydrothermal eruption: landslides in hydrothermal areas	$P_{hydrothermal\ eruption} = 42\%$
Phase II		
Node 1	Appearance of Lp/hybrid earthquakes	$P_{unrest} = 100\%$
	Large regional earthquake	
	Detectable deformation	
Node 2	*Magmatic unrest*: detectable HCl; Island-wide surface deformation	$P_{magmatic\ unrest} = 82\%$
	Hydrothermal unrest: Anomalous behavior of Boiling Lake	$P_{hydrothermal\ unrest} = 13\%$
		$P_{tectonic\ unrest} = 5\%$
Node 3	*Magmatic eruption*: phreatic activity	$P_{magmatic\ eruption} = 53\%$
	Hydrothermal eruption: NO anomalies detected	$P_{hydrothermal\ eruption} = 3\%$
Phase III		
Node 1	Detectable deformation (subsidence)	$P_{unrest} = 100\%$
Node 2	*Magmatic unrest*: detectable HCl	$P_{magmatic\ unrest} = 70\%$
	Hydrothermal unrest: NO anomalies detected	$P_{hydrothermal\ unrest} = 8\%$
		$P_{tectonic\ unrest} = 22\%$
Node 3	*Magmatic eruption*: NO anomalies detected	$P_{magmatic\ eruption} = 17\%$
	Hydrothermal eruption: NO anomalies detected	$P_{hydrothermal\ eruption} = 2\%$

5.1. Phase I

The Phase I exercise inject reported the monitored activity in Southern Dominica in a virtual time period covering 10 months (July 2014 to April 2015; Table 1). The monitoring data showed a significant increase in seismicity in Southern Dominica starting in August 2014, at depths of about 2–3 km and magnitudes up to 3. Hydrothermal observations indicated a small increase in the acidity of the springs in the Valley of Desolation and the Sulphur Springs and no significant variations were noticed in the temperature of waters and fumaroles. GPS measurements revealed a temporal evolution during the reporting period of a northward movement by most stations accompanied by a shortening of baseline length in the southern sector of Dominica in the area of the Boiling Lake, Valley of Desolation and Soufrière. The vertical displacement was of a few mm above background. Reported visual observations included landslides and new hydrothermal vents in the Valley of Desolation that coincided with a high level of seismic activity in November 2014 (Table 1).

The probabilities provided by BET_UNREST (Table 3, Figure 3) are reported for May 2015. They refer only to the nodes up to the vent location (for magmatic or hydrothermal eruptions). The monitoring data presented in Phase I exceeded the preestablished thresholds for unrest, thus the average probability of *unrest* was immediately at 100% (Table 3). The average probability of hydrothermal unrest was 62%, significantly higher than the average probability of magmatic unrest which was 26%; this is due to the fact that the anomalies observed were more consistent with the indicators of hydrothermal rather than magmatic unrest as determined during expert elicitation. Although the probability of magmatic eruption was relatively low ($P_{magmatic\ eruption} = 6\%$, reflecting no anomalies recorded for this node) the average probability of hydrothermal eruption was 42%. The highest probabilities of vent opening were around the Plat Pays and Valley of Desolation areas, and were based on the localization of two monitoring parameters: *new* [*geothermal*] *vents/fumaroles* and *landslides in hydrothermal areas* (Table 3). The average probabilities discussed above were associated with fairly large uncertainties, as shown by the tenth and ninetieth percentiles in Figure 3.

The Scientific Team received a full report on the averages, medians and tenth and ninetieth percentiles of the computed probability distributions for each node. The BET_UNREST results were deliberated by the Scientific Team, but were not reported to ODM as the probabilities were considered "too high." The main reasoning behind this argument was the fact that there was not enough information from the monitoring data to substantiate such probabilities. The report presented to the civil authorities by the Scientific Team at the end of Phase I interpreted the activity in the inject as reflecting "elevated above background" activity, and included recommendations to intensify monitoring (e.g., more frequent water and gas sampling; drone flights for visual observations) and to raise the alert level from "green" to "yellow."

5.2. Phase II

The exercise inject in Phase II reported on the next 7 months of activity, from May to November 2015 (Table 1). During this period the seismic activity shifted to be mainly beneath the Plat Pays and Boiling Lake areas. Seismicity fluctuated during this period but did show an overall intensification, and was dominated by shallow VTs and hybrid events. In September 2015, most of the events were too small to be located. On 21 November 2015, an explosion occurred in the Boiling Lake/Valley of Desolation area, with erupted products having 1–5% volume fresh glass. The inject bulletin stated that hydrothermal activity returned to background levels following the explosion. There were no significant changes in deformation signals over the 7 months period, except during the eruptive event and during one period of drainage of the Boiling Lake (Table 1).

BET_UNREST probabilities are reported for the month of December 2015 (Figure 3; Table 3). During Phase II, P_{unrest} remained at 100%, with the $P_{magmatic\ unrest} = 82\%$ and $P_{hydrothermal\ unrest} = 13\%$. Given the intensification of activity in the Boiling Lake/Valley of Desolation area, the probability of a new vent opening to produce a magmatic explosion increased to 53% and the probability of a hydrothermal explosion dropped to only 3% (Table 3, Figure 3). The probabilities of the magmatic branch were generally higher due to the presence of parameters strongly suggestive of "magma-on-the-move" at these nodes, i.e., *detection of* HCl and *island-wide deformation* (*5–6 cm*). The only anomalous indicator of impending magmatic eruption was *phreatic activity*; as, from the expert elicitation, this was considered a strong precursor for a magmatic eruption in southern Dominica.

The probabilities related to the hydrothermal branch remained low due to the fact that the draining/filling behavior of the Boiling Lake could not be counted as anomalous, since the lake is known to have undergone significant variations in water level and even complete drainage at intermittent intervals in the past [*Fournier et al*., 2009]. The vent location probability map (for both types of eruption) indicated the highest probabilities of vent opening in the Valley of Desolation area; this primarily reflects the location of the reported explosion (Figures 4a–4d). As above, the probabilities obtained are associated with a fairly large uncertainty, primarily because of the use of mostly Boolean parameters and the small number of observed anomalies. With only one or two parameters observed at each node, the uncertainty could not have been reduced without corroboration from other monitored signals.

In Phase II, both the Scientific Team and the BET_UNREST results agreed upon the presence of magma near the surface and a significantly higher likelihood of having a magmatic eruption in the near future. As in Phase I, however, the probabilities were the subject of intense debate among the scientists, and were again not reported to the ODM. The report presented to the civil authorities by the Scientific Team at the end of Phase II interpreted the activity in the inject as reflecting new magma having ascended beneath the Valley of Desolation area and then stalling at shallow depths ($\sim$1 km). Recommendations included the restriction of access to the Boiling Lake/Valley of Desolation area, and that the alert level should be raised to "orange."

5.3. Phase III

The third and final phase of the simulation exercise provided data for monitored activity between December 2015 and July 2016 (Table 1). Following the explosion in the Valley of Desolation area in November 2015, the seismic activity changed from VT dominant to hybrid dominant. Starting April 2016, the seismicity signal decreased steadily until July 2016 when it stopped completely. Geochemical monitoring showed that the activity stayed at background level during the reporting period. Deformation signals showed significant ground subsidence ($\sim$2.5 cm) over this time frame, until July 2016 when inflation started again.

The probability estimates for August 2016 (Table 3, Figure 3) decreased significantly, reflecting the pattern of decreasing activity. The only high probabilities were $P_{magmatic\ unrest} = 70\%$ and $P_{magmatic\ eruption} = 17\%$; these are influenced by the parameter *detectable* HCl which is a strong indicator of shallow magma degassing. During this phase, no anomalies were detected in the hydrothermal branch of the event tree, thus the probabilities related to a hydrothermal manifestation of the system remained low ($P_{hydrothermal\ unrest} = 8\%$ and $P_{hydrothermal\ eruption} = 2\%$).

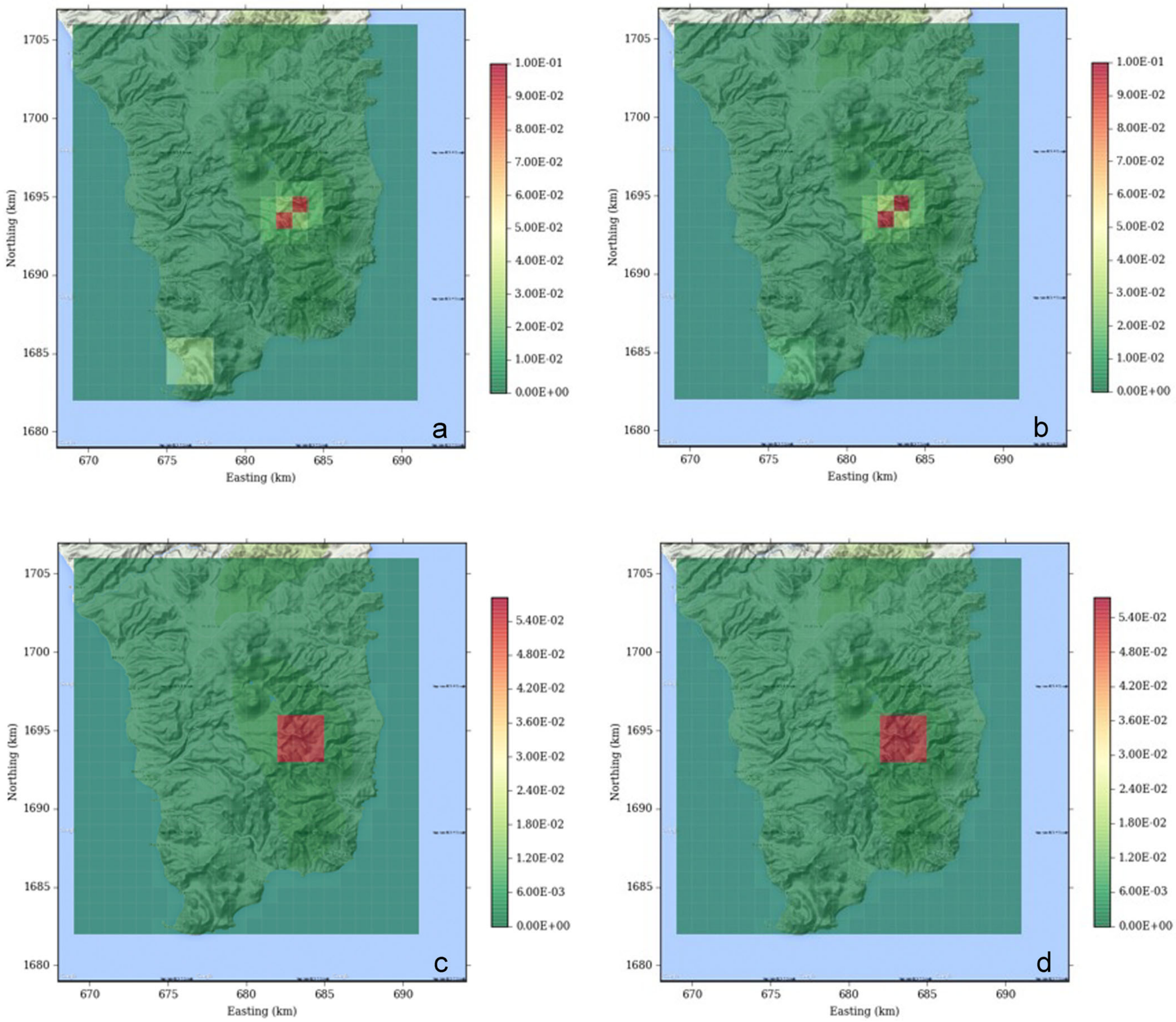

Figure 4. Maps illustrating the probability of vent opening, conditional to eruption occurrence, provided by PyBetUnrest. (a) map of the probability of vent opening obtained during Phase I for magmatic eruption; (b) map of the probability of vent opening obtained during Phase II for hydrothermal eruption, (c) map of the probability of vent opening obtained during Phase II for magmatic eruption; and (d) map of the probability of vent opening obtained during Phase II for hydrothermal eruption. The conditional probability is represented by color-coded gradient.

Based on the monitoring information provided in the exercise inject for Phase III, the Scientific Team concluded that, although the geochemical data had returned to background levels, geochemistry alone could not conclusively say whether the system was no longer displaying continued magmatic or hydrothermal unrest. Conceptual models of the seismic data suggest a deeper source (~10 km) than Phase II, and the Scientific Team concluded at this stage that the unrest episode was not over, given the continuous pressurization of the system. The report presented to the civil authorities by the Scientific Team at the end of Phase III presented two possible scenarios: either the system will recharge and stabilize, or, the system will recharge at depth and will successively follow a similar pattern to the one described in Phase II (e.g., increased seismicity, dyke emplacement, and explosion) maybe even across a shorter period of time. Probability estimates at the end of Phase III again raised controversy within the Scientific Team, and, as in the earlier two exercise phases, were not passed on to the civil authorities. Instead, the Scientific Team conducted a "vote" among the leaders of the geochemistry, geodesy and seismology teams on the probability of a magmatic eruption in the next 6 months, and reported this to be 50%, with an eruption in the next seven days having a significantly lower probability. The Scientific Team recommended continuous monitoring of the area, and a drop in alert level to "yellow."

6. Discussions

The VUELCO Dominica exercise is the first occasion where probabilities obtained using BET_UNREST model have been considered in deliberations of the Scientific Team. This provided us with a unique opportunity to not only test the real-time function of the model and its software implementation PyBetUnrest, but also to observe how the Scientific Team understood and used its results.

6.1. Performance of the New PyBetUnrest Code

PyBetUnrest software provides a user-friendly interface to BET_UNREST model and its setup can be easily updated during a volcanic crisis. The inclusion of the nonmagmatic unrest allows for a more comprehensive probabilistic analysis of volcanic systems, with the aim of integrating information derived from multidisciplinary observations. The software has been implemented in the Python programming language and includes a Graphical User Interface to support the analysis, following the same approach used for the PyBetVH software [*Tonini et al.*, 2015]. The software calculates probabilities in a runtime of a few seconds (it can increase to a few minutes if the number of vent locations is greater than several hundreds) and allows interactively selecting and visualizing the results corresponding to different branches of the event tree. This makes it easier to also quickly get and control the time evolution of the forecast, by, possibly, regularly updating the input coming from new observations (monitoring data).

6.2. The Use of PyBetUnrest Outputs in Scientific Debate During a Crisis

The overall purpose of PyBetUnrest during the Dominica Exercise was for it to be used as a tool to assist the Scientific Team by providing an "extra data set" based on a series of parameters and related thresholds they had decided on in advance.

Interestingly, in all exercise phases, the numerical outcomes (probabilities) of PyBetUnrest raised controversy among the Scientific Team, were often considered as being "too high," and were not included in any of the reports presented to ODM. The controversy likely stems mostly from the fact that, in reality, the deliberation process was based on deterministic interpretation of data, and not all the people involved in the exercise were familiar with the use of probabilities in hazard assessment. Another factor that may have influenced the reluctance to accept the high probabilities could be the fact that Dominica has not seen a magmatic eruption in a long time and the monitoring data did not offer conclusive evidence for magmatic involvement. One of the major issues observed during the exercise is that once the first probabilities were considered too high, the Scientific Team decided to rerun PyBetUnrest, by altering the "basic rules of engagement" and using the information in a different way. Ironically this resulted in even higher probabilities. This "rerunning of the tool" is not necessarily a bad approach, since in reality the human mind is far more flexible than the rigidity of a computer code. Nevertheless, if it is unanimously decided to rerun PyBetUnrest, it is advisable to run the original version along with the modified one, then compare and discuss results. However, it also goes against the very basic rule of BET tools, which is that the input is agreed upon by the monitoring experts far in advance of a crisis. The purpose of conducting numerous elicitation sessions is to allow scientists a "stress-free" environment where they can discuss every possible scenario and provide their "best guess" for the monitoring data and its interpretation. Despite being subjective, the choice for monitoring parameters and their associated thresholds is left up to the experts. Thus, in this case, prior to the "crisis" in a "nonstressful" environment the experts decided upon specific thresholds, and during the "crisis" the same experts reconsidered their thresholds. Such actions affect the practicality of the tool and reflect on the final outcomes, a situation which in reality should be avoided. For example, during deliberations at the end of Phase II, there was an intense debate in the Scientific Team around the detection of HCl, and whether or not it was indicative of magma involvement. In the PyBetUnrest setup, "detectable HCl" was included as a parameter strongly indicative of magma involvement. This resulted in high probabilities of magmatic eruption in Phase II. However, the Scientific Team dismissed the "detectable HCl" as strongly indicative of magma as it was not corroborated by other geochemical signals, and thus also dismissed the probabilities during this phase as they were deemed to be too high. This debate around the obtained probabilities during an exercise is valuable and can lead to useful refinement of the parameters and thresholds, but we suggest that these modifications should not be carried out during the high-stress environment of an actual application, but rather afterward, with incremental refinements and associated further testing ultimately leading to a robust, tested setup.

In retrospect, we acknowledge the fact the elevated probabilities during Phase II might have been the result of cumulated factors such as (1) the limited number of anomalies observed at each node (i.e., the more parameters become anomalous, the more the uncertainty decreases), (2) the appearance of a highly weighted parameter indicative of magmatic eruption (i.e., "detectable HCl"), and (3) the assumption of a high prior model at the "magmatic eruption node" (i.e., 64% of magmatic unrest at complex volcanoes leads to an eruption) [*Phillipson et al*., 2013]. The exercise thus allowed us to identify potential flaws in the design of the event tree, which can be refined in order to improve the scheme for future applications.

6.3. Use and Understanding of Uncertainties

In general, the uncertainties related to the average probabilities provided by BET_UNREST were dismissed by most of the Scientific Team. The BET Group observed that this was not done on purpose, but given the stressful crisis environment and need for rapid decision making, people tended to look for confirmation of their opinions and, if this was not the case, then the numbers were easily dismissed. Uncertainties cannot, however, be excluded from deliberations, since the usefulness of the BET_UNREST models is to offer a clear quantification of uncertainty. This is in fact a measure of the reliability of the average probability. Probabilities were indeed high, but were, on each occasion, associated with a large uncertainty (Figure 3), stemming from our poor understanding of Dominica's magmatic-hydrothermal system and the modest monitoring network, resulting in high epistemic uncertainties. The uncertainty is a fundamental part of the Bayesian approach and should thus be considered in any evaluation. One interesting fact is that, at the end of the reported period of Phase II, the Scientific Team decided that new magma had been injected in the system and the probability of a magmatic eruption was high. At the same time, BET_UNREST offered an average probability of magmatic unrest of 82% and magmatic eruption of 13%, which concurs with this opinion, yet the probabilities were still not trusted. The difference between the two was the "measure" of uncertainty provided by the BET_UNREST model, that the scientists could not, leaving the interpretation presented to the ODM to be based more on "gut feelings and experience," despite the fact that a more quantitative option with uncertainties was available.

Overall, the probabilities obtained with the help of PyBetUnrest were high and the magmatic branch was favored, but this is likely because in reality any volcanic activity is driven by magma at different depths and sometimes it is hard to distinguish magmatic from hydrothermal unrest, especially in short time frames. During the exercise, despite the fact that both the Scientific Team and BET Group agreed on magma involvement and significant probabilities of magmatic eruption, there was a clear split between a probabilistic interpretation of the monitoring data and a classic deterministic-based one (i.e., experts in different fields like geochemistry, seismology and geodesy track the changes in volcanic activity and then discuss until they come up with a "single opinion" which does not always reflect any measure of uncertainty). BET_UNREST model provided a high average probability but acknowledged the large uncertainty around it, and this forced the intense deliberation around scientific opinions derived from a deterministic analysis.

7. Conclusions and Recommendations

During the Dominica VUELCO exercise we were able to observe the pros and cons of using a probabilistic model in the decision-making process during a volcanic crisis. We conclude that the BET_UNREST application itself was successful and brought the tool one step closer to a full implementation. We were able to identify the flaws in our assumptions for the event tree that will help us improve the model for future use. At the same time, we were able to observe how probabilities obtained with computer software are perceived by the scientists involved in the exercise, and how they may influence the deliberation process. However, as with any newly proposed method it needs more testing, and in order to be able to use it in the future we make the following recommendations:

1. In order to effectively implement BET_UNREST model in the decision-making process of a real situation, we suggest that all members of the scientific group should be aware of how it works and how it provides

the results. This should reinforce the fact that its software implementation PyBetUnrest is an "assisting tool," one of many in the volcanological toolbox, capable of offering a visual and palpable estimate of the probabilities of particular outcomes and the uncertainties related to our poor knowledge of the system. It offers a probability of the most likely outcome, out of the many possibilities, provided that the input data are of high quality. Hence, in order to improve its results, all effort of the experts involved in the elicitation should focus on providing reliable input information. It is not a tool that "gives the best and final results," it should not be seen as a tool to "confirm scientists' opinions," nor should it be seen as a competing opinion [see *Rouwet et al*., 2016a]. It is our opinion that the results obtained with BET_UNREST should be included in the reports transmitted to the authorities as they offer a measure of uncertainty, regardless of the numerical value they have. Any interpretation should not take probabilities as definitive but as additional information to the traditional data (i.e., geodetic, geochemical, and geophysical) that usually "supports" the decision making.

2. A very important aspect of a functioning BET_UNREST model is the definition of the monitoring parameters, thresholds and inertia. The overall philosophy of the model is to allow users to contemplate all these aspects long before the crisis so they can agree on a "best estimate" of the volcano in question. This exercise showed that no matter what parameters and thresholds were considered as being "best" and "straightforward" in a nonstressful situation, opinions might change during a crisis. Thus, if the code is tweaked, this will influence the final probabilities produced by the code. We strongly suggest that parameters should be defined in such a way as to accommodate the flexibility of the human mind. Appropriate definition of the "rules" of the BET_UNREST model can accommodate this flexibility in the interpretation of monitoring data. For example, the "detectable HCl" parameter had to be included in BET_UNREST as it was set up during five elicitation sessions, yet the Scientific Team did not use it as indicative of magma involvement in their final recommendations. Perhaps if the parameter were defined differently, to accommodate human flexibility, it would have led to more acceptable results. In volcanic environments with sophisticated monitoring networks, the use of fuzzy parameters that allows tracking the degree of an anomaly by using ranges of values (i.e., lower and upper threshold) is recommended.
3. During a crisis in which BET_UNREST is employed, we recommend that the Scientific Team be flanked by an objective BET usage, that is an application of the code in which it is ran according to its preestablished "rules-of-engagement," with monitoring information from the volcano during the crisis, in order to provide probabilities accordingly, without allowing the code to be tinkered with. The Scientific Team should be aware of how the model is set and works, to identify the rare occasions when possibly new knowledge or new insights may need to be accommodated in the model's rules. However, if the situation deems the modification of the event tree adopted necessary, it is recommended that the original code be run along with the modified version/s, and the results then compared and discussed. In this case, careful and written notes of all modifications must be kept, to maintain full transparency.

Although in the end the probabilities obtained with BET_UNREST were not included in the final reports that the Scientific Team forwarded to the civil authorities, they were included in the deliberations. The controversy around the probability estimates is actually considered as a success, because it highlighted the "real" problems that occur when scientists involved in deliberations are faced with such numerical data. The important thing is to take advantage of these lessons and conduct more tests that will eventually improve BET_UNREST design and lead to a full "real-case" implementation.

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