Probabilistic eruption forecasting and the call for an evacuation

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Short title: ERUPTION FORECASTING AND EVACUATION

Abstract. One of the most critical practical actions to reduce volcanic risk is the evacuation of people from threatened areas during volcanic unrest. Despite its importance, this decision is usually arrived at subjectively by a few individuals, with little quantitative decision support. Here, we propose a possible strategy to integrate a probabilistic scheme for eruption forecasting and cost-benefit analysis, with an application to the call for an evacuation of one of the highest risk volcanoes: Vesuvius. This approach has the following merits. First, it incorporates a decision-analysis framework, expressed in terms of event probability, accounting for all modes of available hazard knowledge. Secondly, it is a scientific tool, based on quantitative and transparent rules that can be tested. Finally, since the quantitative rules are defined during a period of quiescence, it allows prior scrutiny of any scientific input into the model, so minimizing the external stress on scientists during an actual emergency phase. Whilst we specifically report the case of Vesuvius during the MESIMEX exercise, the approach can be generalized to other types of natural catastrophe.

Introduction

There is an exceptional class of extreme rare natural hazard events which pose a critical evacuation dilemma for civil protection officials, and the scientists who advise them. A common feature of these events is that they threaten the lives of many hundreds of thousands of people, whose evacuation from danger would be logistically complex and uncertain in its effectiveness and duration. Another feature of these events is that the complexity of the processes involved make a deterministic functional prediction (i.e., with a leading time long enough to take some practical actions) an unreliable goal [*Sparks*, 2003]; in general, scientists have some forecasting skill at providing timely warnings, but these are subject to a significant risk of false alarms.

In a meteorological context, an example would be a Category 5 Atlantic hurricane track potentially heading towards Manhattan, but which might veer seawards. Compared with Hurricane Katrina, which claimed 1500 lives, the longer return period of this scenario creates a vastly greater challenge in evacuation decision-making. In a volcanological context, the most celebrated example of a colossal evacuation problem would be that of an eruption of Vesuvius (see http://www.protezionecivile.it/cms/view.php?dir_pk=395&cms_pk=3323&n_page=4), overlooking the populous Bay of Naples (see figure 1). The fact that the size of an imminent eruption is almost indeterminate and it cannot be predicted by the precursory activity [*Marzocchi et al.*, 2004] makes any evacuation decision in a volcanic crisis especially fraught. As part of the preparedness for an extreme natural hazard event, it is prudent to test the evacuation decision-making process itself, along with the logistics of the evacuation process. Apart from learning what technical improvements need to be made in monitoring and communications to support an evacuation decision, the actual criteria used for decision-making can be scrutinized. As a major experiment in critical evacuation decision-making, the recent MESIMEX exercise carried out at Vesuvius (http://www.protezionecivile.it/cms/view.php?dir_pk=395&cms_pk=3323) offers some special scientific insights.

Here, we use this exercise as a tutorial example to describe a new procedure that links eruption forecasting and cost/benefit analysis to provide a quantitative and objective rule for taking the "optimal" decision. In the following sections we describe the methodology and the a posteriori application of the procedure to MESIMEX.

The method: probability of event and cost/benefit analysis

Forecasting is a fundamental goal of modern volcanology. Civil authorities and the public need to know when (and sometimes where) the eruption will occur, the size of the event, and the kind of distinctive phenomena that might occur. Forecasting is only one of many issues that authorities in charge of managing volcanic emergencies have to take into account in taking any risk-based decision or action. Emergency management involves a complex interplay between social and economic needs, and the infrastructure capability needed to sustain them. In particular, it is necessary to evaluate the vulnerability of exposed infrastructure, facilities and property, the impact of eruptions on human beings, costs vs. benefits of proposed mitigation measures, and the level of acceptable risk for society. In addition, we need educational programs to improve the risk perception of the people living around volcanoes [*Davis et al.*, 2005], and improved ways to communicate risk and associated uncertainties to those people, mass media, and local authorities.

In this compound framework, the role of volcanology is mostly focused on providing a reliable eruption forecasting in terms of probability of some specific event of practical interest. Whilst it is natural that scientists averse to speculation should wish to be confident in an event forecast, and false alarms are detrimental both to scientific reputation and public trust, the minimization of the false alarm rate is not an optimal decision criterion where many lives are at risk, and the probability distribution for mass evacuation duration has a long tail [*Woo*, 2007].

A decision to evacuate in the face of an uncertain threat from a volcano falls within a common important category of economic decisions: pay a price now to avert paying a larger price later, contingent on the occurrence of an uncertain hazard event. The significant socio-economic expense of evacuation is the premium deemed worth paying so that, in the event of a volcanic eruption, the much higher cost of mass casualties is avoided.

The economic character of this class of decisions is exemplified by the basic cost-loss model [*Katz and Murphy*, 1997]. Consider a situation where a decision-maker has to choose between two actions: (a) protect; (b) do not protect. The cost of protection is $\mathcal{C}$. In the absence of protection, the decision-maker incurs a loss $\mathcal{L}$, which exceeds $\mathcal{C}$, if an adverse hazard state arises. Let the probability of the adverse hazard state arising, within a specified time window, be denoted by p. If the expected expense is to be minimized, then the optimal policy is to protect, if $p > \mathcal{C}/\mathcal{L}$, but not to protect if $p < \mathcal{C}/\mathcal{L}$. The minimal expense is then $\min\{\mathcal{C}, p\mathcal{L}\}$.

In a volcanological context, protection would be evacuation, which carries a cost of $\mathcal{C}$. Note that in this case, as well as in all other circumstances where the decisions are taken under uncertainty, the cost $\mathcal{C}$ has to properly include also the tangible (e.g., income lost) and intangible (e.g., lost of credibility) cost of false alarms. The adverse hazard state here is one of volcanic eruptivity, for which a decision not to protect carries a large loss penalty of $\mathcal{L}$, measured in human fatalities. Civil protection officials would wish their scientific advisors to be sure of their forecasts, which could then be dependably followed in decision-making. However, in the real world of uncertainty, every evacuation decision involves weighing the advantages against the disadvantages. This balance of judgement is customarily assessed subjectively, if earnestly, by civil protection officials. Thus, prior to the landfall of Hurricane Katrina, New Orleans Mayor Ray Nagin worried over the city being sued if a mandatory evacuation turned out to be unwarranted [*Brinkley*, 2006]. Typical of urgent natural hazard crises, only hours were available to deliberate the pros and cons. Whereas it is always the prerogative of civil protection officials, who carry the burden of public responsibility, to judge the cost-benefit ratio $\mathcal{C}/\mathcal{L}$, and so establish a criterion for p, this ratio is amenable to a substantial degree of quantitative analysis, which can be conducted systematically for decision-makers well in advance of any crisis [*Woo*, 2007]. To do justice to the complexity of the technical issues involved may take man-years of inter-disciplinary research effort by economists, social psychologists, transportation engineers as well as volcanologists. Such extensive analytical study by many professional experts may currently be telescoped into a few short hours of pressurized crisis deliberation by public officials.

Where evacuation cost is mostly measured in terms of economic loss, and non-evacuation loss is measured in excess lives lost, then an upper bound for $\mathcal{C}/\mathcal{L}$ can be obtained assuming a minimal value of a fatality, such as is used in public policy studies. Where a significant proportion of evacuees would owe their lives to an eruption, this upper bound may turn out to be quite small, equivalent to the probability p being well below evens. In such circumstances, procrastinating an evacuation decision until scientists become confident in their forecast is tantamount to under-valuing human life. For the Vesuvius case, acknowledging the stated priority of Italian Civil Protection authorities to safeguard human life, the implementation of a cost-benefit criterion for evacuation decision-making would allow this principle to be reconciled in a measured rational way with the known public intolerance of false evacuation alarms.

The application to MESIMEX

MESIMEX (Major Emergency Simulation Exercise) was a simulation carried out between the 17th and the 23rd of October 2006 by the Regione Campania (administrative institution of the region that includes the Neapolitan area) and the Dipartimento Nazionale della Protezione Civile (Italian Civil Protection), with the goal of testing and improving the coordination among national and European institutions, the organization of civil protection operations, and the preparedness of civil society, in case of an eruption at Vesuvius.

The core of the scientific part of the exercise was the definition of a realistic pre-eruptive scenario for Vesuvius, simulated by a pool of experts. The activity included several typical phenomena accompanying volcanic crises, such as seismic activity, deformations, gravity changes, etc. The second part of MESIMEX was devoted to an evacuation exercise as established in the Emergency Plan. In particular, a sample of two thousand people were evacuated from the Red Zone, that is the area most likely threatened by pyroclastic flows of a sub-plinian eruption, which represents the reference scenario in the Emergency Plan. As regards the pre-eruptive phase, information on the simulated activity of the volcano was dispersed within the scientific community through a series of bulletins (one or two per day) distributed through a mailing list and a dedicated internet blog.

These bulletins were used as scientific input for a software code, called BET_EF [Bayesian Event Tree for Eruption Forecasting; *Marzocchi et al.*, 2004; 2007], designed to track the time evolution of the probability of eruption. The code, based on a Bayesian procedure, accounts for all the relevant available information, such as theoretical models, a priori beliefs, monitoring measures, and past data, in providing the probability of the event of interest. A full description of the code and of the application to the MESIMEX exercise can be found in *Marzocchi et al.* [2007]. Here, in figure 2 we report the time evolution of the probability of eruption and of the occurrence of a sub-plinian or larger event. The latter probability is particularly crucial for societal risk, because the most threatening effects, namely the occurrence of pyroclastic flows, are mostly linked to the occurrence of sub-plinian or plinian events [*Marzocchi et al.*, 2004]. The graph of figure 2 displays a monotonic increase of probability of eruption and pyroclastic flow occurrence, with a marked jump, describing the time evolution of the pre-eruptive phase approaching the event. With this perspective, MESIMEX has pioneered the real-time quantification of eruption probability for scientists to gauge the dynamical evolution of the volcanic threat.

Due to its experimental nature, and to the difficulties to project a continuous numerical probability value into a binary evacuation/no evacuation decision, the BET_EF results were not considered for decision-making during MESIMEX. As a matter of fact, the evacuation recommendation by the scientists was subjectively issued when the assessed probability of an imminent eruption given by BET_EF had surpassed 0.8, indicative of a high degree of confidence in threat realization. However, as mentioned above, the choice to minimize the probability of false alarm is not the optimal one when many lives are at risk. As an explicit example of the method described above, figure 2 illustrates the hypothetical case where decision makers choose to use a threshold value for p (probability of pyroclastic flow occurrence) of 0.1 for calling an evacuation. As discussed in detail by *Woo* [2007], such a threshold estimate would arise if about 10% of evacuees would owe their lives to an evacuation call, and a standard minimum economic value is placed on human loss; note that, in this scheme, higher percentages of saved lives imply lower probability thresholds. For these reasons, we think that such a threshold could be a reasonable value for the case of Vesuvius. Anyway, we stress again the tutorial nature of this example, and, as mentioned before, that the real threshold has to come out from a cost/benefit analysis carried out by Civil Protection. If we assume that an evacuation aims mostly to protect people from the occurrence of pyroclastic flows, we note that such a probability exceeded the threshold after the fourth bulletin, i.e., much before the time in which the evacuation was really called (after the sixth bulletin). In this case, the evacuation would have been called with larger uncertainty about the actual evolution of the volcano (in other words, with a higher probability of false alarm), but it would have afforded more time to the Italian Civil Protection to protect the citizens in threatened areas.

Final Remarks

As a special experiment in critical evacuation decision-making, MESIMEX has proved to be a very instructive exercise, that has allowed a large number of scientific/technical procedures to be tested. The usual strategy adopted during a volcanic crisis is to fall back on the subjective opinions of a pool of experts, with less attention paid to quantitative volcano risk metrics. Through MESIMEX, a basic obstacle has been identified obstructing the use decision-makers may gain of probabilistic forecasting information: mapping continuous probabilities into a binary evacuation/no evacuation decision. The development of a cost-benefit framework to implement this mapping enables probabilistic forecasting tools, such as the one provided by BET_EF, to be used more effectively to improve evacuation strategies.

Acknowledgments. This work was funded by the Italian Dipartimento della Protezione

Civile in the frame of the 2004-2006 Agreement with Istituto Nazionale di Geofisica e Vulcanologia - INGV. The authors thank Dr. Vilardo of INGV-Osservatorio Vesuviano for providing the picture of Vesuvius.

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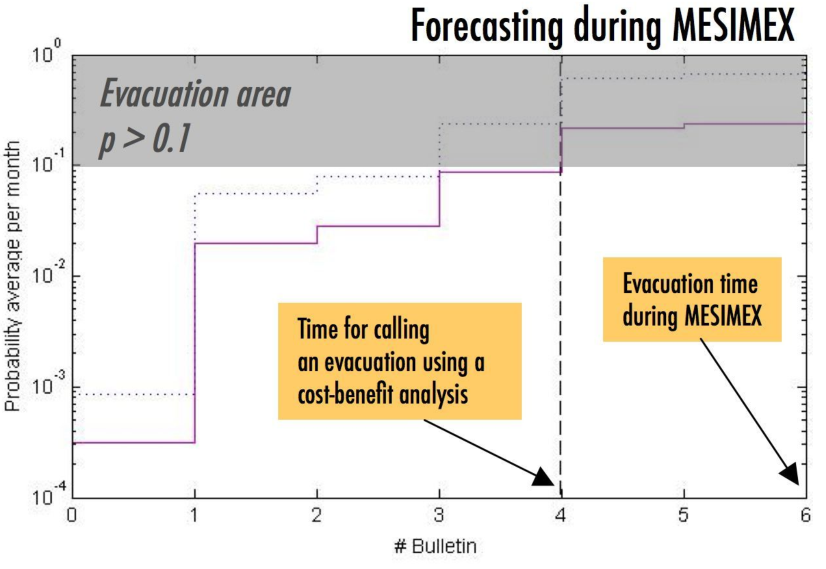
Received ; revised ; accepted .

Figure 1. The Vesuvius with the so-called Red Zone, that is the area that has to be evacuated in case of a call for an evacuation during a volcanic emergency. This area contains about half a million people.

Figure 2. Plot of the time evolution of the probability per month of eruption (dotted blue line) and of pyroclastic flow occurrence (solid violet line). The x-axis reports the number of the bulletin; the origin (Bulletin number 0) represents the probabilities calculated during a quiet phase of Vesuvius. The upper grey area represents the evacuation area, i.e., when the probability is greater than the tutorial threshold 0.1 obtained by a hypothetical cost-benefit analysis that, in real cases, must be carried out by Civil Protection.


Forecasting during MESIMEX
Evacuation area
p > 0.1
Probability average per month
10^0
10^-1
10^-2
10^-3
10^-4
Time for calling
an evacuation using a
cost-benefit analysis
Evacuation time
during MESIMEX
0
1
2
3
4
5
6
Bulletin