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Communicating likelihoods and probabilities in forecasts of volcanic eruptions

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ABSTRACT

The issuing of forecasts and warnings of natural hazard events, such as volcanic eruptions, earthquake aftershock sequences and extreme weather often involves the use of probabilistic terms, particularly when communicated by scientific advisory groups to key decision-makers, who can differ greatly in relative expertise and function in the decision making process. Recipients may also differ in their perception of relative importance of political and economic influences on interpretation. Consequently, the interpretation of these probabilistic terms can vary greatly due to the framing of the statements, and whether verbal or numerical terms are used. We present a review from the psychology literature on how the framing of information influences communication of these probability terms. It is also unclear as to how people rate their perception of an event's likelihood throughout a time frame when a forecast time window is stated. Previous research has identified that, when presented with a 10-year time window forecast, participants viewed the likelihood of an event occurring 'today' as being of less than that in year 10. Here we show that this skew in perception also occurs for short-term time windows (under one week) that are of most relevance for emergency warnings. In addition, unlike the long-time window statements, the use of the phrasing "within the next…" instead of "in the next…" does not mitigate this skew, nor do we observe significant differences between the perceived likelihoods of *scientists* and *non-scientists*. This finding suggests that effects occurring due to the shorter time window may be 'masking' any differences in perception due to wording or career background observed for long-time window forecasts. These results have implications for scientific advice, warning forecasts, emergency management decision-making, and public information as any skew in perceived event likelihood towards the end of a forecast time window may result in an underestimate of the likelihood of an event occurring 'today' leading to potentially inappropriate action choices. We thus present some initial guidelines for communicating such eruption forecasts.

1. Introduction

Prior to and during natural hazard events and crises, such as volcanic eruptions, tsunami, earthquake aftershock sequences and severe weather events, scientific and technical agencies commonly issue statements about the likelihood of an event occurring, based on detailed analysis of historic events and current conditions. Over recent years, it has become more desirable for scientists to utilize numeric probability statements to allow objective decisions via quantitative risk metrics such as Bayesian event trees, Monte Carlo analysis, Expert Elicitation and cost benefit analysis. However, probabilistic statements can commonly be misinterpreted, whether they are communicated in a verbal (e.g. using terms like *likely*), or numerical (e.g. using alternatives like 70%) format.

Research into the public understanding of probabilistic phrases has identified that the framing, directionality and probabilistic format of these statements can bias people's understanding, affecting their action choices (Teigen and Brun, 1999; Karelitz and Budescu, 2004; Budescu et al., 2009; Joslyn et al., 2009; Visschers et al., 2009; Lipkus, 2010). In addition, many of these probabilistic and likelihood statements include a specified time window, and it is unclear as to how people rate their perception of an event's likelihood throughout this time frame. In a crisis situation, this can result in costly and inappropriate decisions due to a misinterpretation of a probabilistic statement and thus an inappropriate assessment of the situation.

In this study, we thus investigate whether people appropriately interpret the likelihood of an event occurring 'today' versus a future date. We next briefly review the key issues regarding the communication of probabilities during a volcanic crisis (Section 1.1), review the lessons from the psychology literature on communicating verbal and

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numerical probabilities (Section 1.2), and discuss the use of probabilistic forecast time windows in volcanology (Section 1.3). This is followed by an introduction to the understanding of probabilities and time window forecasts in volcanology (Section 1.4), and an explanation of the survey method used for the study (Section 2). We then present the results from this multi-part online survey to examine the effects of wording and profession (*scientists* and *non-scientists*) on people's perceived likelihood of a volcanic event occurring, based upon a series of likelihood forecasts (Section 3). This is followed by a discussion of the potential implications and reasons for the skew in perception observed (Section 4). Finally, we conclude with some initial recommendations for the communication of probabilities and forecast time windows in volcanology.

1.1. Communicating during a volcanic crisis: the case of probabilities

Successful emergency management decision-making during a volcanic crisis is fundamentally dependent upon the situational awareness of the emergency manager, both as individuals and as a team (Endsley, 1997; Martin et al., 1997; Crichton and Flin, 2002). This is their assessment and understanding of the available information, the definition of the problem at hand, and the time and risk pressures. Developing this initial and ongoing situational awareness is critically dependent upon the information and advice from science advisors and observatories, and the quality of shared mental models developed in both training and effective team based simulations (Cannon-Bowers and Bell, 1997; Crego and Spinks, 1997; Paton et al., 2000; Pliske et al., 2001; Borodzicz and van Haperen, 2002). An individual's mental model of the hazard itself, defined by Bostrom (2008, p. 308) as "how people understand and think about the hazard, and their causal beliefs", will then interplay with any shared mental models about response and communication. The communication of risk information between emergency managers and the public, or scientists and emergency managers is also subject to the *mental models gulf* (Morgan et al., 2002), whereby there is a gap between "what experts know and the plan they develop, versus what key public know and prefer" (Heath et al., 2009, p 129).

Thus, the quality of dialog and information provision depends upon individuals' mutual understanding of the needs, responsibilities, demands, and roles of each party, and their capacity to anticipate other parties' demands and decision needs (Salas et al., 1994; Lipshitz et al., 2001; Paton and Jackson, 2002; Doyle and Johnston, 2011). This process works well with objective information (e.g., when describing the action of ash on buildings). However, the probabilistic data (e.g., how much ash and when and where it will be distributed) communicated from scientists to emergency decision makers is more open to interpretation, particularly in high stress response contexts (Paton and McClure, 2013). The reason why stems from differences in how scientists and practitioners relate to, interpret, and respond to hazard information. Training, professional memberships, and experience result in people developing interpretive frameworks and mental models, used by people to interpret, explain and then plan for and make decisions about volcanic crisis events (Fischhoff et al., 1982; Johnson-Laird, 1983; Bostrom et al., 1992; Atman et al., 1994; Werner and Scholz, 2002; Zaksek and Arvai, 2004). The scientists who conduct hazard analyses and provide science input during a volcanic crisis and the emergency managers who use scientific information to develop their response plans are influenced by different mental models and thus how these events and relationships are interpreted.

Scientists translate their findings about hazard activity (e.g., ash fall) into probabilistic statements (i.e., statements that reflect some interpretation) using their accumulated knowledge of hazard behaviors (e.g., return periods and historical patterns of intensities). Based on their training, however, emergency management professions use scientific data to determine whether or not they need to do anything and, if they do, to determine what they should do and when they should do it. Scientists will give the highest weighting to volcanic hazard data, whereas emergency managers will, particularly in the context of making high risk/high cost decisions (e.g., evacuation) place additional emphasis on political and economic criteria as, for example, they attempt to reconcile hazard data with the pragmatics of evacuation decisions and the costs and consequences that this would bring.

Information provision and science advice are key components of the initial situation assessment and ongoing situation awareness of these key decision makers and emergency managers during a volcanic crisis (see Doyle and Johnston, 2011, for a more comprehensive review). However this advice is subject to many levels of uncertainty, due to the natural stochastic uncertainty (the variability of the system) and the epistemic uncertainty (lack of knowledge) (van Asselt, 2000; Patt and Dessai, 2005). To address the many uncertainties inherent in the data involved in the assessment and management of volcanic eruptions, due to their complex nature, precise prediction is not achievable and necessitates the use of probability statements in the scientists' communications and forecasts about these dynamic phenomena (Sparks, 2003). A wide range of methods are used within volcanology to statistically analyze time series and other available data, and to calculate the probabilities of a future eruption occurring (see Mader et al., 2006, for an example collection). These are based on geophysical data and the understanding of the physics of the governing processes (Sparks, 2003), where short term forecasting can be based upon monitoring of characteristic geophysical and geochemical signals. Alternatively, forecasting methods range from an analysis of historical records of volcanic eruptions to calculate probabilities of future eruptions based upon a statistical analysis of inter-event times (see Bebbington and Lai, 1996; Connor et al., 2006; Turner et al., 2008), through to the development of Bayesian event trees that estimate the progress from the general probability of unrest through to more complex events such as the probability of specific hazards after eruption has occurred (see review in Marzocchi et al., 2006).

When calculating forecasts and estimating the probabilities or likelihoods of future events, complications arise in that our epistemic uncertainty results in unknown parameters and physical processes, which can make a "frequentist" approach to forecasting challenging, particularly for previously dormant volcanoes that may be unstudied with little knowledge about the eruption history. The use of alternative methods such as Bayesian approaches enables the calculation of probabilities of future events to be based not only on past observations, but to be updated as additional data and knowledge becomes available. Recently, there has also been a move to include pre-defined thresholds of probability based on a cost benefit analysis, prompted by a desire to make objective decisions via quantitative volcanic risk metrics (Marzocchi and Woo, 2009). Cost–benefit analysis tools (Marzocchi and Woo, 2007), and the use of forecasting systems such as Bayesian event trees for eruptions (Newhall and Hoblitt, 2002; Marzocchi et al., 2004; Woo, 2008; Sobradelo and Marti, 2010) are viewed as being highly advantageous for the decision-making process of the scientists, as they clarify decision thresholds as well as optimizing the decision-making time, offering the hindsight ability to clearly explain how a decision was made (Lindsay et al., 2009; see also recent reviews in Donovan et al., 2012; Marzocchi et al., 2012), and offering a way to enhance mitigation decision processes (e.g. Baxter et al., 2008). However, while this approach facilitates scientists' decision making, its impact and influence on non-scientific users of this information remain to be ascertained.

The importance of systematically investigating the latter derives from the fact that the outcomes of such tools often include probability terms that are then used in communications with key decision makers. The International Association for Volcanology and Chemistry of the Earth Interior Subcommittee for Crisis Protocols (IAVCEI Subcomittee for Crisis Protocols, 1999, p. 330) has established guidelines for communication in a crisis that recommend the "use of probabilities to calibrate qualitative assessments of risk". However, a number of studies have identified that qualitative, non-technical statements are often preferred by non-scientists due to a limited understanding of concepts such as probabilities (e.g. McGuire et al., 2009). Haynes et al. (2008, p. 263)