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Modelling risk and risking models: The diffusive boundary between science and policy in volcanic risk management

Amy R. Donovan *, Clive Oppenheimer

Department of Geography, University of Cambridge, Downing Place, Cambridge CB2 3EN, United Kingdom

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ABSTRACT

This article examines the science–policy interface in volcanic risk assessment. It analyses empirical data from research on Montserrat, where new volcanic risk assessment methodologies were pioneered. We discuss the ways in which these methods contributed towards the ordering of scientific advice in its geographical context, and we provide examples of the complex and overlapping topologies that are assembled in a volcanic eruption. In this case, the science–policy interface can be conceptualised as diffusive: both science and policy contain multiple overlapping networks of actors, objects and ideas that interact with one another through flows of responsibilities, attribution, identity and interpretation. Volcanic risk management involves negotiation of conceptual, relational and physical boundaries, and as a result requires the use of qualitative and quantitative methods across human and physical geography.

Introduction

Disaster risk reduction research is increasingly seeking to be holistic and to approach the planning for and mitigation of disasters from top-down and bottom-up, but it is sometimes hindered by relative disengagement with the science–policy interface. The formula that risk is a combination of hazard and vulnerability reflects a focus in disaster studies on the latter, and a focus on the former in scientific research. However, the interface between hazard and vulnerability is much less well studied, yet can play a critical role as scientific hazard assessment may be used in government decisions that seek to reduce vulnerability. Scientific advice in disasters is increasingly recognised as an important area of study. It will always been needed urgently in volcanic crises (perhaps more so than for other hazards), and populations can become dependent on science overnight when volcanic unrest begins and there is a time-critical need for information about likely scenarios (Donovan et al., 2013). Gaillard and Mercer (2013) further argue that scientific knowledge must be integrated with local knowledge in the risk assessment process, and Lane et al. (2011) have demonstrated the impact that this can have on both the process of assessment and its social reception – popular conceptions of risk may differ significantly from those of scientists. Such emerging methods are important in managing the science–policy interface, but raise epistemological questions about the nature, remit and, critically, limits of (social and physical) scientific knowledge when it is used to inform policy.

An example of this arises in the use of scientific models in the management of natural hazards through land zonation. While scientific modelling has a great deal of value and power for understanding the possible trajectory of a hazard event and estimating its likelihood, the use of models by experts and decision-makers is also a social activity with potentially significant social impacts, and the ontological basis for the scientific modelling may not be in accord with social perceptions of space and identity. Models have a role in communication with populations, for example, but as soon as they are used in this way their vulnerability as representations of nature is exposed. The use of scientific models in the communication of risk and uncertainty has been discussed at length in the literature on climate change (e.g. Wynne and Shackley, 1994; Shackley and Wynne, 1995; Demeritt, 2001; Demeritt et al., 2010, 2013; Hulme and Mahony, 2010; Hulme, 2009), and models are increasingly used to inform decision-making regarding natural hazards (e.g. Demeritt et al., 2010, 2013; Demeritt and Nobert, 2011; Kuhlicke and Demeritt, 2014; Nobert et al., 2010). Models seek to bring a level of order to the natural system in order to replicate its behaviour, but their application to the social system via lines on hazard maps is complicated by social, political and economic considerations relating to property and business and by different ideas about space and identity (Donovan et al., 2012a). In part, this relates to the different ways that people conceptualise their spatial context (e.g. Haynes et al., 2007). However, it also has wider ramifications in terms of national

* Corresponding author.
E-mail address: ard31@cam.ac.uk (A.R. Donovan).

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identity, human rights and political responsibility: land and identity, particularly on small islands, may be closely entwined (e.g. Skelton, 2000). This means that scientific advice about areas as safe or unsafe can have wide-reaching consequences for geographical imaginations.

In this paper, we reflect on the use of scientific models in volcanic risk assessment and management on the island of Montserrat, a UK Overseas Territory in the West Indies, analysing the implications for science and policy on active volcanoes. Volcanic eruptions on Montserrat occurred episodically between 1995 and 2010 (Druitt and Kokelaar, 2002; Wadge et al., 2014), requiring long-term risk management, particularly in the demarcation of evacuation zones. In this article, we initially examine the epistemological basis of models and then contextualise these within the science and policy literature on reflexivity and boundary work. Empirical data from Montserrat is presented, concerning the scientific basis for pyroclastic flow models and their development, and scientists' and locals' views about modelling and about the broader political context. The models were used alongside expert elicitation and Monte Carlo simulation to produce risk assessments that fed into the drawing of boundaries on maps (Wadge and Aspinall, 2014). Finally, we draw out some broader themes from this discussion, arguing that the philosophical, political and psychological factors involved in the complex negotiation of risk assessments create qualitative uncertainties that can be acknowledged through narratives. This requires a reflexive, self-conscious and transparent approach, and one that is geographically sensitive. At a very broad level, it also presents an important opportunity for geographical reflection on the nature of space–time-risk relations: volcanoes and volcanic eruptions can be viewed as assemblages. They are affected by and themselves affect the histories and geographies of groups of people, objects and ideas who may be connected in different, overlapping ways. They also provoke new associations of ideas and actors – including models that gain a level of agency in the decision-making process.

Theoretical framework

In this section, we first examine the different ways in which models are conceptualised in the literature. We discuss scientific use of models as means of representing and ordering the natural system, and note the power of representation among scientists, showing the impact of the social context on the ways in which models are designed and used. We then focus on the implications of this for studies of space: models seek to bring order to nature, to enclose it within human frameworks. In contrast, human geographers have argued that space cannot be enclosed. Juxtaposing these ideas provides some insight into the challenge of integrating scientific assessments and policy decisions about land use. We therefore move on to consider in more detail the literature on boundary work and boundary objects in the context of science and policy. We argue that geographical understandings of reflexivity and boundary work can elucidate the challenges faced by scientists in risk assessment under uncertainty. Furthermore, the use of models as a means of ordering the science–policy boundary changes their nature: they become open to controversy in a way that perhaps undermines the act of ordering itself. In the context of hazard mapping, this is the result of the difficulty of bringing order and enclosure to spaces that resist them.

We use the idea of diffusivity as a way to represent the spreading out of ideas, objects and actors across these artificial boundaries of science and policy. Another way to conceptualise this might be to use the geographical theory around topology and assemblages: volcanoes can be viewed as assemblages that incorporate multiple impacts, interpretations, ideas, objects and people. These are different types of thing, but they relate to one another in ways that are contingent (DeLanda, 2006). Relational topologies exist within science and within policy, but also between them – and power can diffuse through these relations. However, as McFarlane (2009) notes, "refusing to use scalar concepts is a fruitless strategy given the prevalence of scalar narratives": similarly, refusing to accept that there are felt conceptual boundaries – and boundaries on maps – is impractical. However, the idea of diffusivity can be a link between these two conceptualisations, as the forces of responsibility, knowledge, blame, ownership and identity (among others) "spread out" through different types of connections. This paper focuses tightly on the relationships between scientific models and decision-making about land use, and it demonstrates the complexity of negotiating volcanic risk in its social context. In doing so, however, it also points to the potential contribution of an integrated geographical approach to volcanic risk management.

Models in environmental science

Models as sources of geographical narratives have been discussed by a number of authors (e.g. O'Sullivan, 2004): models involve stories about potential futures, sometimes of particular places. Recent studies of modelling practices within Geography have elucidated their complexity and variety – and the draw of new models that look impressive (e.g. Hulme and Mahony, 2010; Mahony and Hulme, 2012; de Chadarevian and Hopwood, 2004; Demeritt and Wainwright, 2009). Even prior to the recent debates, Shackley and Wynne (1995, 1996) discussed the use of climate models as "boundary-ordering devices", seeking to bring order to the threat of chaos on the interface between uncertain science and policy in trying to manage future risks.

Within science, models may simultaneously represent the best science and be highly uncertain (e.g. Oreskes et al., 1994). They can be conceptually very different, yet represent the same physical processes. Giere (2004) notes that:

> Scientists use models to represent aspects of the world for various purposes. On this view, it is models that are the primary (though by no means the only) representational tools in the sciences.
>
> [2004:747]

In constructing his "cognitive theory of science", Giere (1988, 2004, 2006), Callebaut (2012) argues that scientific models are dependent on the judgements and thought-processes of the scientists who develop them. Models, in this view, are representations of nature that carry with them some characteristics of their human origin.

An interesting example of the representational power of models concerns an outdated conceptual model that has proved persistent. Kagan et al. (2012) note that in spite of extensive scientific evidence a number of concepts persist in the seismological literature. They focus on the "characteristic earthquake model", which posits that faultlines have "characteristic earthquakes" that occur periodically and represent the maximum likely magnitude for the faultline. This has been challenged by extensive data analysis, yet scientists "continue to use buzz phrases grounded in once-prevalent paradigms that have been subsequently refuted". They suggest in conclusion that "the time for case studies, anecdotes, speculation and Band-Aids for failed models has passed...otherwise earthquake science will not deserve the name". This is an acknowledgement (by scientists) of the power of representation within science – and the assertion that it is unscientific. This follows from recent debates about what constitutes "science" in hazard assessment for Earth Sciences (e.g. Castanos and Lomnitz, 2002), and the increasing role of models in risk and hazard assessment necessitates further discussion of the philosophy of modelling and method.

From this perspective, Oreskes et al. (1994) argued that the verification of models in the Earth Sciences is impossible; O'Sullivan (2004) describes this claim as "irrefutable". In setting out a "preliminary agenda" for science studies in geography, Wainwright (2012) identifies modelling as a critical issue because of the complex dialogue between scientific practice and modelling practice. He further notes the importance of particular places in the making of science – an issue dealt with by historical geographers of science (e.g. Livingstone, 2003, 2005; Powell, 2007, 2008; Withers et al., 2006). Massey (1999) argues that in her conceptualisation, "'space' cannot be a closed system". The act of reclaiming models for geographical purposes is thus one of "opening up", epistemologically and spatially (Stirling, 2008). For Massey, space is dynamic: it must be thought of in relation to time. It resists enclosure in a model. In considering geographical models in light of this, O'Sullivan (2004) suggests that "it is vital that modelling is not left to the modellers" (291): the stories inherent in the models are worthy of telling. This includes the provenance, assumptions and limitations of the models, and the social implications of their use.

It follows from the above that (i) scientific practice is not purely objective but encounters both social and political influences, particularly where it is envisaged as policy-relevant, (ii) scientific models are heterogeneous, partial representations of reality, (iii) a single model is only part of the picture and may require high levels of judgement about not only input parameters but also about context, conceptualisation and dimensions – about which scientists may not agree and (iv) models are of great interest to human geographers both in terms of the stories about nature and space that they represent, and in terms of their social and political contexts. In the next section, we link these ideas with literature that discusses the ways in which models and other "objects" may be used by scientists and policymakers to negotiate boundaries.

Uncertainty, reflexivity and "boundary work"

It is customary to separate "risk assessment" from "risk management", ideally lining these up with "scientist" and "policy-maker" respectively and thereby retaining neutrality for scientists. This is akin to the "linear model" for the science–policy interface, which has been shown to be flawed by numerous studies (e.g. Owens, 2005; Fischer, 2000; Pielke, 2004): the interface between science and policy is diffusive. Political factors affect the ways in which scientific reports are framed, for example, just as politicians' interpretation of scientific information will affect the decisions that are made (e.g. Jasanoff, 1990, 2004, 2005): scientific reports and risk decisions are co-produced (Lövbrand, 2011; Kuhlicke and Demeritt, 2014). Coproduction occurs through the negotiation of uncertainty and authority in attempts to make evidence-based decisions, and it occurs as scientists and policymakers engage in boundary work.

The Science Studies literature refers to three different but overlapping concepts – "boundary work" (Gieryn, 1983), "boundary objects" (Star and Griesemer, 1989) and "boundary-ordering devices" (Shackley and Wynne, 1996). Gieryn (1983) used "boundary work" to describe practices employed by scientists to delineate their own disciplinary territory, and guard it against infiltration from policy or social groups. It is ultimately a means of claiming scientific authority and credibility. "Boundary objects" are those that seek to enable communication across groups, such as between scientists and the public, so that these groups can work together; an example of a boundary object might be an alert level system, such as the Hazard Level System on Montserrat (Donovan et al., 2012a), which is discussed below. Shackley and Wynne (1996) refer to "boundary-ordering devices" as types of boundary object that are short-lived or serve a particular purpose at a particular time. The example they apply is that of representations of uncertainty in climate change models, which negotiate between the authority of science and its potential undermining by uncertainty.

Arguably, probabilistic risk assessments are boundary-ordering devices, managing the grey zone between empirical science and risk policy. On Montserrat, there have been two main methods that might constitute this kind of work. Models have been used to define lines on maps, and expert elicitation (e.g. Aspinall et al., 2002; Cooke, 1991; Aspinall and Cooke, 1998) has been used to provide probabilities (and uncertainties) of the events represented by the lines (e.g. Aspinall et al., 2002; Wadge and Aspinall, 2014). These maps and probabilities can then be applied in the political management of the hazards. The problem with the application of technologies like mapping to the management of hazards is that they undermine any distinct boundary between science and policy, because lines have to be drawn somewhere. While scientists may argue that they are scientific because they follow the flow runout from models, populations may argue that the results depend on the inputs, and directly affect their ability to get house insurance, for example.

Science thus affects and is affected by its context. In examining this, we turn to the social scientific idea of reflexivity. The concept of reflexivity in the social sciences has been described by Lynch (2000) as "used in a confusing variety of ways". In part, this stems from the same duality of meaning as noted by Beck (1999): reflexive practice in research involves a self-consciousness, while reflexive actions may also be unconscious. Thus Bourdieu (2004) refers to reflexivity as a "mirror effect" (2001:4). Lynch (2000) suggests that some practitioners apply reflexivity as a means of "increasing objectivity" in their research. He goes on to produce an inventory of reflexivities, demonstrating the many uses of the term and the potential inadequacy of self-consciously reflexive research. In this article, we take reflexivity to mean a self-aware analysis of the role of the practitioner in the results of the research. As such, it is also a means of managing social uncertainties.

Brown (2010) has argued for a more open treatment of uncertainty in environmental research, noting the presence of social, psychological and geographical uncertainties (see also Stirling, 2007, 2008; Wynne, 1992; Jasanoff, 2004, 2005, 2007; Pidgeon and Fischoff, 2011; Richards et al., 1997; Power, 2007). Understanding the complex ways in which uncertainty is generated is critical in appreciating the social and political implications of scientific work. In this article, we examine the rapid development of scientific models alongside an evolving political situation in a particular place. We suggest that not only do *both* qualitative and quantitative expressions of uncertainty play a key role, but also that a reflexive, contextualised approach to risk assessment requires that scientific models and data be used in a distinctive way and with a deep consciousness of psychological, political and philosophical influences on method and interpretation. The liminal nature of risk assessment – not only between scientists and policymakers, but often on the edge of scientific philosophical boundaries – necessitates a broader discussion of meaning and uncertainty in understanding the co-production of science and social order (Jasanoff, 2004).

Boundaries – spatial or conceptual – are vulnerable things. Human geographers have argued that space cannot be bounded, and that geography itself is fundamentally uncontainable – it is constructed of networks and flows that are not readily pinned down (Amin, 2004, 2007). Space is relational, not scalar. The relational turn in geographical thinking (e.g. review in Jones (2009)) presents an important opportunity for the geographies of science and Science Studies. The use of models as a form of representation, communication and of social adjustment is fundamentally relational. Models, methods, reports, laws, social, political and scientific networks are all linked through their collective role in managing an eruption. Furthermore, the level of influence that each has on the process can be regarded as a diffusion of power and ideas. For example, while a report is written by scientists, using scientific language and based on scientific data, it is read by policymakers and the public with their own cultural and experiential background. It is not retained within a bounded entity that can be called "science" because it has a social origin and a social role, and it generates ideas and impacts that percolate into policy and populations.

This paper therefore draws on the Science Studies literature in a particular geographical context, and in doing so it argues that a geographical gaze can exert considerable power in understanding not just the nature of "boundary work", but also its problems: boundaries are contingent and socially constructed. They are inevitably transgressed through the interconnected ideas, objects and actors that refuse to remain in one camp or another. Scientific networks grasp ideas and concerns that are political, social or economic, while policymakers learn to "decode" scientific information and make judgements about its validity themselves. Boundaries, like models, are representations that are open to interpretation and interrogation. Geographical approaches can thus bring considerable insight into the complex topologies of representation in the management of risk on active volcanoes.

Local context and methods

Following the Emergency Powers Act of 1996, the Governor of Montserrat had the power to order mandatory evacuations, in consultation with the local government (through a committee latterly known as the National Disaster Preparedness and Response Advisory Committee, or NDPRAC), and based generally on scientific advice. In order to facilitate such advice, the Montserrat Volcano Observatory (MVO) was established in 1995 (Aspinall et al., 2002; Donovan et al., 2013). In addition, senior academic scientists were involved in providing advice to the Governor's Office – in 2003, this group was formalised as a Scientific Advisory Committee (SAC). Prior to 2003, it was known as the Risk Assessment Panel (RAP). Many of the scientists involved with the SAC also carry out extensive research on Montserrat. During the period covered in this article, the SAC was meeting every six months. The MVO and the SAC together included Caribbean scientists, European scientists and US scientists with varying levels of experience and involves geochemists, geophysicists and geologists. There has been no official involvement of social scientists in the risk assessments on Montserrat.

A series of articles in *Nature* in 1998 gave a high profile to the challenges faced on Montserrat by scientists, and the extent of public trust (e.g. Masood, 1998; Aspinall et al., 1998; Voight, 1998). In particular, the need to communicate "uncertainty and doubt" was expressed, amidst accusations that the locals' predictions were on a par with the scientists'. This continued to be a theme: throughout the evacuation from October 2002 to July 2003, for example, the *Montserrat Reporter* carried articles, letters and limericks about the inadequacy of the science, and a case was brought against the Governor by a group of local residents (Aspinall and Sparks, 2004; Donovan et al., 2012a). Even where these represented an extreme minority view, they were nevertheless symptomatic of tensions and suspicions that pressured scientists. (For detailed discussions of changing identities on the island, see Skelton, 2000, 2003.) This politicising of volcanology can be challenging for both sides. On Montserrat, it has been complicated by the difficult transition from an acute crisis mentality in government and society to the appreciation that the eruptions may continue for decades and should be regarded as a "chronic" problem for planning purposes (Donovan and Oppenheimer, 2014). Managing this transition has required consistent yet innovative approaches to scientific modelling and to scientific reporting (Aspinall et al., 2002; Loughlin et al., 2010; Wadge, 2009; Donovan et al., 2012b,c,d). The negotiation of boundaries took place between the roles of the local government and the UK government (on Montserrat and in Whitehall), between scientists and policymakers, between physical science and probabilistic approaches to risk assessment and between the MVO and the SAC. Below, we use an example of rapid evolution of physical models that were used in probabilistic risk assessment to analyse the nature of these boundaries and the ways in which they were negotiated – particularly those between science and policy.

This article draws on interviews of local residents, scientists and government officials in Montserrat and the UK, and participant observation carried out at the Montserrat Volcano Observatory between 2008 and 2009 in two ten-week field seasons, including attendance at two meetings of the Foreign and Commonwealth Office Scientific Advisory Committee on Montserrat Volcanic Activity. In total, 62 semi-structured interviews with government officials (10), scientists (21) and residents (31) were carried out. Questions were open to allow interviewees to share their experiences freely. Participants were selected according to their role or through contacts in local businesses (by snowballing in order to gain a varied sample of stakeholders, some of whom were "remote" from the usual; e.g. Atkinson and Flint, 2001). This included key decision-makers in the Montserratian government and representatives of the UK government on the island. In addition, extensive documentary research was undertaken at the Montserrat Volcano Observatory. All the qualitative data were coded by themes that arose from the dataset itself. The large volume and diversity of data gathered and analysed in this project required that codes be relatively simple and broad (e.g. Somekh and Lewin, 2005). Quotations in the text are from the interviews unless otherwise stated. An indication of the role of participants is given, but owing to the small number of people involved, a detailed account would breach confidentiality. In this paper, we focus on the perceptions that scientists had of local people's views. Quotations are selected because they are representative of themes within the dataset as a whole.

The 8th January 2007 event on Montserrat

This section discusses an example from Montserrat concerning the application of scientific models at a time when modelling capacity was developing rapidly and in dialogue with an evolving risk management issue. It seeks to demonstrate empirically the argument of the theoretical discussion above: that risk assessment is a social process as well as a scientific one, and that its diverse epistemologies require contextualisation of both qualitative and quantitative uncertainties through reflexive narratives that allow for the multifaceted, connective nature of risk. This process acknowledges that scientific assessment cannot truly be independent of its political implications, and there is a level of diffusion between science and political decision-making, through the involvement of human actors, impacts and ideas throughout the process.

An example of the links between physical danger, scientific risk assessment, the delineation of boundaries and national identity was provided by one long-term resident:

> *...the people who have come, I don't believe have any desire to go to Plymouth. They don't have any desire to go south of Belham, because everything is north – they work in the north, they live in the north, Brades – the government headquarters – is in the north ... they haven't lost what most of us have...*

This sets the broad geographical context for the detailed analysis of the science–policy interface that follows: it shows that spatial restrictions, imposed by the volcano via scientific advice and political decision-making, had lasting impacts on the way that people thought about Montserrat's identity. The population is essentially divided between those who remember Montserrat pre-1995, and those who do not – with the latter continually increasing in number. Lines on maps affect the ways in which people think about places. This demonstrates the importance of understanding the generation of such lines and the complex, intertwined topologies with which they interact. This paper now examines one aspect of this problem – the relationship between scientific models and public policy.

Models in volcanology

Interviews with scientists confirm that modelling results are known within the scientific community to be interpretations and not facts. There is a degree of subjectivity involved – a choice of the best-fit model does not equate to the actual system; it approximates it. Judgement calls in modelling are also made concerning the use of discrete and continuous variables, and dimensionality – indeed, even in risk maps it has been argued that gradation should be continuous rather than discrete, an issue raised by interviewees (see also Haynes et al., 2007). Increasing complexity may increase accuracy at the same time as increasing uncertainty. Testing of a model using actual events provides some measure of the reliability of the model, but is dependent on the availability of data (Spiegelhalter and Riesch, 2011; see also Oreskes et al., 1994). The use of diverse input parameters is further complicated by divergent interpretations of events that have been observed. The eruption of 8th January, 2007, for example, may or may not have had a small explosive component, and may or may not have originated in the dome itself.[1] This demonstrates the importance of combining information from multiple sources in risk assessment:

> *It goes back to philosophy of science... for hazard purposes ... the attitude should be that all interpretations of the data are valid unless you can demonstrate they're not... the multiple-working-hypothesis syndrome is extremely important in hazards because even if you think that one interpretation is the best one, you should actually include all of the other alternative interpretations because they might have hazard or risk implications.*
>
> [Senior scientist, SAC]

This represents a desire to manage the uncertainty involved in hazard assessment by maximising the volume of information available, and including all non-falsified interpretations. It also shows the inherent uncertainty in the decisions about which models to use, and suggests a difference between science "for hazard purposes" and research: the context affects the ways in which science is applied.

Volcanologists have devised a range of methods for modelling pyroclastic flows (e.g. Wadge et al., 1998; Widiwijayanti et al., 2004, 2009; Esposti Ongaro et al., 2007, 2008). Some of these models are based on "semi-empirical" databases of past flows, while others are purely dynamical, based on simplified representations of flow over topography. In the following section, we give an example of a specific case in which models of pyroclastic flow run-out informed the quantitative risk assessment process. In response to the dome collapse and generation of pyroclastic flows towards inhabited areas on 8th January 2007, a major initiative to estimate future hazards was undertaken, alongside a well-established elicitation method for assessing likely frequency, and the number of models used increased – this diversity is part of the process of including all of "the other alternative interpretations". Probabilistic hazard models were combined with assessments of frequency and population to estimate risk. The following section thus outlines the dialogue between emerging science and emerging social order. It also shows the complexity of scientific modelling in the context of social anxiety and the history of scientific and socio-political interactions.

The procedural development of scientific models

During the second half of 2006, the lava dome began to grow rapidly. By December 2006 the dome facing the northwest side of the volcano threatened the Belham Valley and the inhabited areas around it (Fig. 1). On 8th January, 2007, a dome collapse sent pyroclastic flows down the Belham Valley as far as Cork Hill (Loughlin et al., 2010). With a large dome that remained and posed a continuing threat on the northwest side, the question of a "safe" line was raised, along with more detailed zonation in the Old Towne-Olveston area. Over a few weeks members of the SAC and colleagues deployed an unprecedented combination (see below) of four pyroclastic flow simulation codes that were used to assess the hazards posed by dome collapse and lateral blast flows in the Belham Valley (Table 1). The 8th January event was used to calibrate the models, but the volume of the dome capable of collapse into the Belham Valley was not accurately known. These models were used to provide hazard lines for the maps (Wadge, 2009; Esposti Ongaro et al., 2008) – challenging because of the high uncertainty in the models, but the authorities "want to know where the line is on the ground" and "the delineation of the boundaries would be set based on these models" (senior scientist).[2]

> *Certainly when the Chief Scientist or director or whoever goes to talk to them after the SAC meeting, the discussions are usually at a fairly basic level, as in, do we have to leave or don't we? ... Is the Belham safe or isn't it... the scientists of course try to draw lines, and they draw fuzzy lines or they draw sharp lines and they draw lines of uncertainty...*
>
> [Senior scientist MVO]

This challenge was also expressed by local officials seeking to create evidence-based policy: the boundaries are based on the models but are officially set by the NDPRAC. This quotation also raises the issue of the conjunction of binary decisions and the more complex probabilistic representation of hazard (Demeritt et al., 2010). These uncertainties complicate public decision-making because they do not sit easily with the realities faced by decision-makers. They also allow a blurring around the process of boundary-negotiation, so that science is buffered from the political.

The continuing requirement that uncertain models be accorded social relevance was a driving factor in the refinement of models during the course of the eruption: policymakers wanted to use the models to set – and justify – the boundaries, while scientists were aware of the uncertainty involved in doing so.[3] For example, SAC 7 (SAC, 2006b) revised the PYROFLOW models in accordance with historical flow directionality (Fig. 2) as the control on how much material travelled in each direction (this had previously been

[1] This event was discussed with interviewees and during fieldwork, and different views were expressed.

[2] In detail, the models allowed the simulation of potential hazard events, and the potential temporal frequency of the hazards was assessed using expert elicitation. The boundary lines on the maps allow the definition of zones, for which individual risk per annum could be calculated based on assumptions of the population of the zones, using the elicitation probabilities and Monte Carlo population impact risk simulation modelling.

[3] This is evidenced in the SAC reports, which continuously develop and refine the models and input data that are used.

Fig. 1. Map of Montserrat, derived from an ASTER image, 2006. Contours (50 m) are derived from an SRTM digital elevation model. The Belham Valley is shown in blue, and the summit of the active volcano is shown as a red triangle. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

based on estimates). However, these simulations (Fig. 2) were effectively limited by calibration to the set of flows with runouts less than about 6 km (maximum onshore runout to date), whilst longer, larger flows were not represented. It was these longer flows capable of reaching 8 km or more down the Belham Valley that were simulated in early 2007, in accordance with scientific judgement that they were important. The rapid evolution of volcanic activity on the north-west side of the volcano in early 2007 also prompted the production of new models for lateral blasts in particular. In February 2007, the MVO asked the SAC for an interim assessment of risk, as

Table 1
Models used on Montserrat during SAC 8.

Model	Physical basis
PYROFLOW (Wadge et al., 1998; Wadge, 2009)	Dynamical – gravity flow + surge component Monte-Carlo ensemble approach can be applied, using observed data from Montserrat to estimate likely future flows (Wadge, 2009)
PFz (Schilling, 1998; Iverson et al., 1998; Widiwijayanti et al., 2009)	Statistical – calculates how a valley will be filled with a particular volume using semi-empirical equations (e.g. Widiwijayanti et al., 2009)
TITAN-2D (Patra et al., 2005; Widiwijayanti et al., 2004)	Dynamical – simulates a granular flow, provides a timeseries of material location areally. Numerical computational simulation using a DEM
PDAC (Esposti Ongaro et al., 2007, 2008)	Dynamical – 3D multiphase flow model; can simulate flows with a blast component

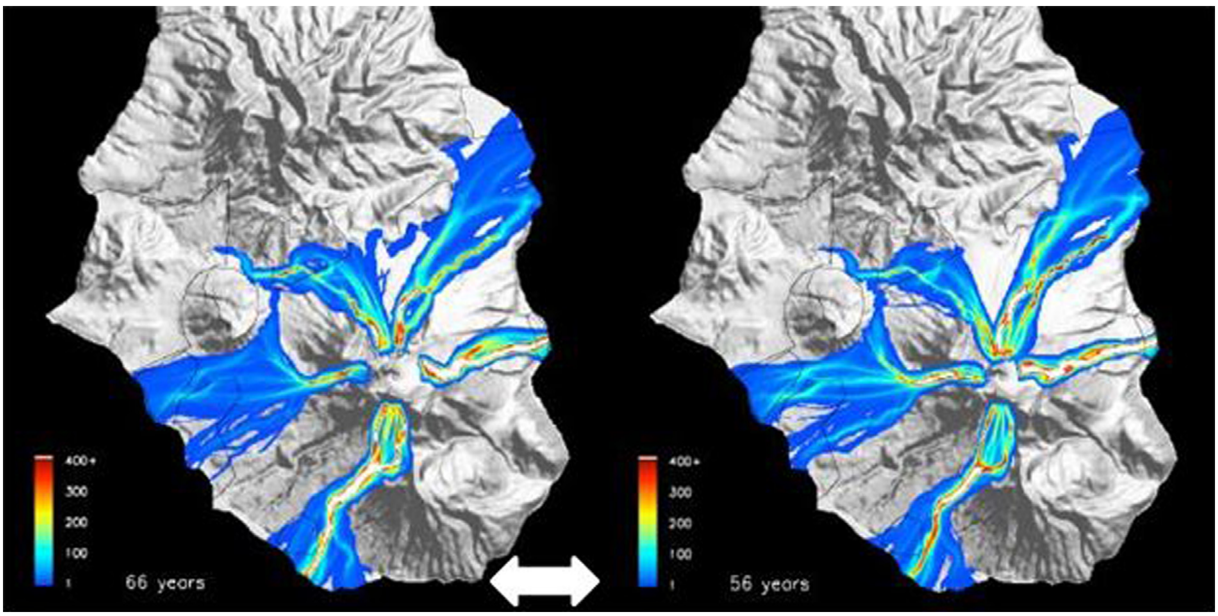

Fig. 2. SAC 7, Fig. 4. Probability of pyroclastic flow inundation using PYROFLOW. The ensemble of simulations shows how often any given spot is inundated in 66 (or 56, right) years of simulated activity of dome collapse flows with runouts less than 6 km. Left result is with directional weighting calculated; right result is from SAC 6 (SAC, 2006a) with directional weighting estimated. The white arrow is approximately 2 km long (no scale on original).

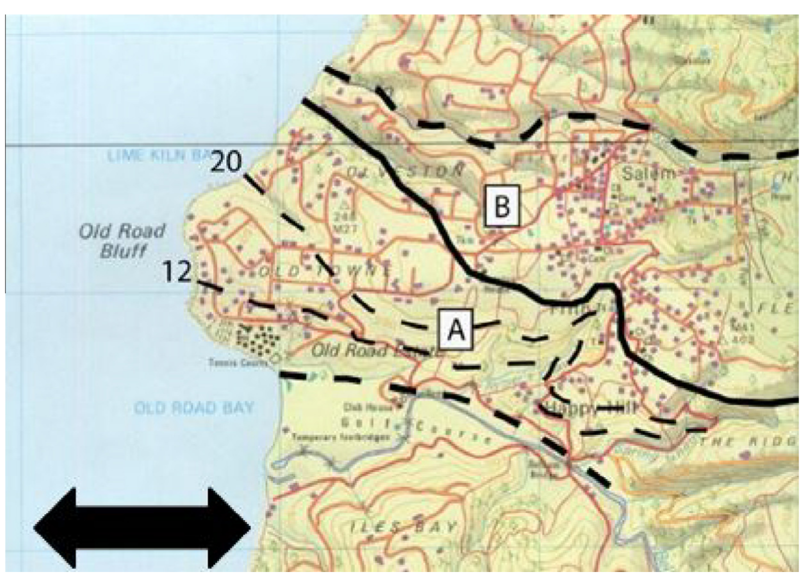

Fig. 3A. Map for February 2007 Interim Assessment. Zones A and B were those provided with probabilistic assessments. The solid black line divides A and B, which are bounded by thick dashed lines. The thin dashed lines are the surge margins of potential dome collapse flows with volumes of 12 and 20 million cubic metres. The black arrow is approximately 1 km (no scale on the original).

the situation had evolved since SAC 7 (August 2006). Fig. 3A shows the zones used for the calculation of individual risk scores. The text of the Interim Report (SAC, 2007a) notes that:

> *These values very much depend on where the line between areas A and B is drawn*. If, for example, the A/B line had followed the 12 million surge line then the individual risk exposure within the smaller area A would have increased.
>
> [italics in original, p2]

This shows that the uncertainty in the location of the lines was an area of concern, because it affected the social data used in the calculation of individual risk per annum: having run the model, the scientists still had to make a decision about where to put the lines for the rest of the assessment – literal "boundary work", and also work that involves uncertain judgement. The report notes in its conclusion that "the current evacuation zone boundary based on the SAC7 report 12 million cubic metre surge modelling has no 'margin of safety' and hence may not be sufficiently cautious" (p3) – a social comment, acknowledging the need for precaution to protect people and perhaps showing the scientists' own perceptions of the risk as higher than it was perceived by the population. This is based on a scientific assessment of the risk, but also an awareness of the use to which that assessment will be put – demonstrating the diffusivity inherent in the use of scientific information for risk management. Interestingly, a UK official stated:

> *The point about the SAC is that it is uninformed by the human geography – it's purely the physical geography. They work out the hard numbers for particular areas if they're asked... they're very good at taking long-term views ... that type of area where a director on a day to day basis might be quite nervous about that... [we get] a different sense of perspective out of the SAC.*

This suggests a view that science is completely separate from the human – and that "hard numbers" for risk exist. Yet at the same time, it also acknowledges the effect of the nature of the request for advice on different groups of scientists with different perspectives. Again, this quotation is indicative of the diffusive nature of the science–policy interface: it shows that people try to separate science from the human, and yet are simultaneously aware of its human aspects.

The March 2007 Interim Assessment (SAC, 2007b), and SAC 8 (SAC, 2007c) (late March 2007) saw the incorporation of new models for dome collapse flows and – for the first time – for lateral blasts. This led to the redrawing of the zone boundaries (Fig. 3B).

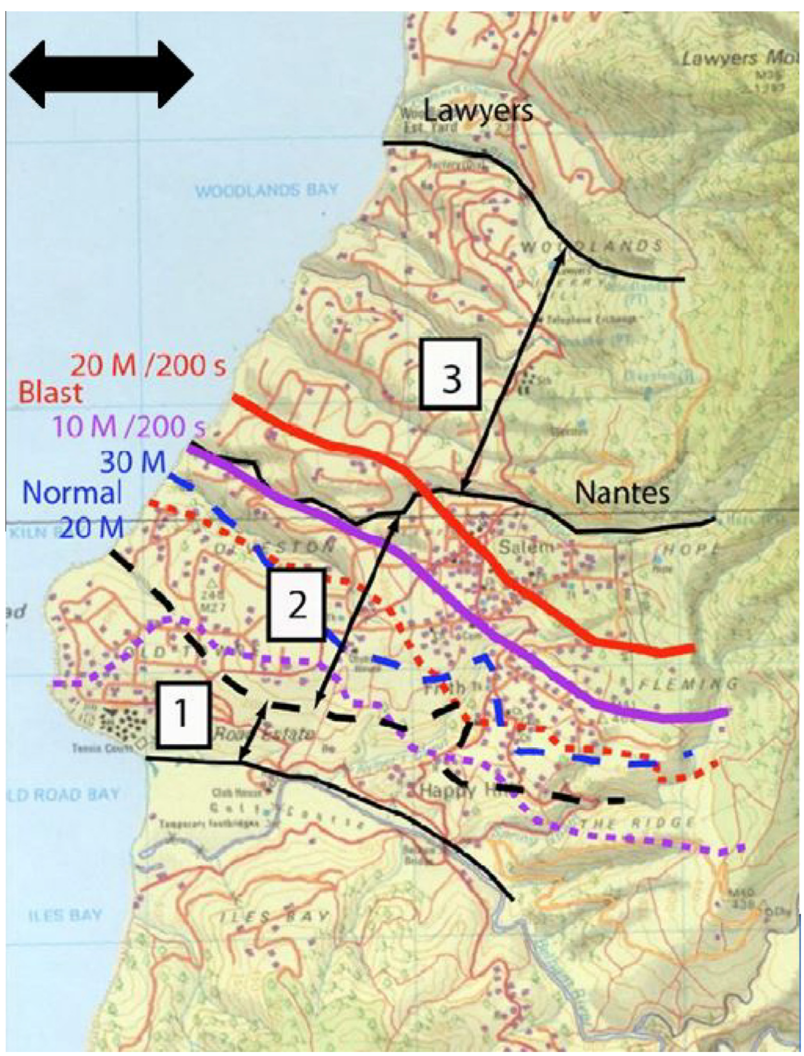

Fig. 3B. Map for March 2007 Interim Assessment, this time using three population zones (1–3, bounded by black thin and thick dashed lines). Coloured lines represent dome collapse ("normal") and lateral blast surge limit runouts by volume as stated (20 M – 20 million cubic metres. Lateral blast scenarios also give arrival times in seconds. These zones were also used in SAC 8. The black arrows are approximately 1 km (no scale on the original). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In contrast to previous assessments (which had applied the PYROFLOW model), SAC 8 used a suite of four different models for pyroclastic flows and lateral blasts – "a pioneering effort" (SAC 8 Technical Report, p 5) during a volcanic crisis (Table 1). All of the models were calibrated using real data from Montserrat. In particular, the PDAC model of a north-directed lateral blast was calibrated using the model parameters for the Boxing Day 1996 blast to the southeast (Esposti Ongaro et al., 2008). This also required that the digital elevation model be kept up to date as the eruption reshaped the topography of the island (a GPS-based survey was carried out on 9th February 2007).

In this case, the new models suggested a significantly higher risk to the population in the event of a lateral blast to the northwest, compared to the equivalent "normal" dome collapse flow; see the equivalent 20 million cubic metre event lines (solid red = blast, dashed black = dome collapse) in Fig. 3B. The increase in calculated risk was a result of the use of the new, more advanced models rather than of the volcanic activity itself, but was felt by the scientists to be a real increase in risk as a result of lower epistemic uncertainty and its impact on the result of the risk assessment. The February interim analysis prompted the evacuation of Area 1 by the NDPRAC (Fig. 3B). The progression of science was directly wired into the change in policy, but the language of the reports seeks to manage the uncertainty inherent within the lines by suggesting options to the authorities – the conclusion of the February report repeats concerns about lines not being "sufficiently cautious" for example, and authorities "may wish to consider" the lines again.

Political challenges and uncertainties

This development of models was itself negotiating between the volcanic activity and the risk that it posed to the population: there was public criticism in local media of the MVO because it was felt by some that the evacuation was unnecessary. Furthermore, the reasoning for the boundaries was not always appreciated by the population:

> *The evacuation lines are so arbitrary. My house could be in the safe zone and that house over there not. I mean literally there are houses next to each other and one had to go and the other could stay, so that creates frustration.*
>
> [Resident, referring to evacuations prior to 2009]

It is interesting to note that this quotation describes the boundaries as "evacuation lines": a reference to their felt effect rather than their empirical origins. The resulting popular frustration tended to affect MVO scientists more than SAC members, although the SAC were very much aware of the problem in interviews. A similar situation had occurred in 2002–3, noted above, and was also characterised by a large dome in the NW. The SAC interim report in February 2007 noted,

> *The level of quantitative analysis that has gone into the current deliberations is greater than 2003.*
>
> [p3]

This demonstrates an awareness of the similarity to the 2003 events, which had caused considerable upheaval – and explicitly seeks to gain authority and objectivity from "quantitative analysis" (a form of boundary work). Rhetoric in the reports includes references to "more sophisticated computer models" and being "at the cutting edge of what is currently technically possible": volcanic risk assessment with direct social consequences was occurring alongside scientific advancement. In recognition of this, the SAC produced a separate document with the March Interim Report. It notes that "all lines on maps marking their (PF) extent should really be thought of as being for very broad guidance" – indicative of scientists' discomfort with the use of the lines administratively and a recognition of their liminal status. It goes on to suggest ways in which the government could mitigate the effects of flows and blasts to the north-west, including risk education using videos of models, alterations to houses and the use of sirens. The basis for this advice is the experience with the models and previous actual events on Montserrat in 1997. It seems to attempt to bring order to the application of the scientific advice by the authorities, and the reaction of the public. Expertise and experience are strongly emphasised, and there are also strong denials of liability (as there are in all SAC reports). A response to the uncertainty about both the science and the public response was to appeal to the authority of science and also to increase the level of social and political comment within the reports. This simultaneously enforced the boundary around the remit of the science, but also indicated the penetration of social concerns through that boundary: the scientists experienced qualitative uncertainties about the likely response of the government to their advice.

There is abundant evidence of the political challenges of risk assessment and management on Montserrat, and the complex boundaries and connectivities involved (Aspinall et al., 2002; Haynes et al., 2007, 2008; Donovan and Oppenheimer, 2014; Pattullo, 2000). Both scientists and officials tended to link the British Government with risk aversion, and the local government with a desire to "keep the island going":

> *The British Government on the whole has been more risk averse than the local population and their political representatives. That's verged on denial at times, particularly early on in the crisis by the local politicians ... basically there was a denial syndrome that something this terrible was happening – and certainly the Government of Montserrat and its chief ministers and politicians have tended to be less risk averse because they want to keep the island going.*
>
> [Senior scientist SAC]

Some interviewees expressed the reasoning they thought was behind the differences:

> *They want to be seen to have their independence. The British Government doesn't want dead people, ultimately, on their hands, that they can be... so they've tended to be more risk averse in their perspective...the difference has occasionally been quite marked.*
>
> [Senior scientist SAC]

The UK and Montserrat governments were thus perceived as having very distinctive risk tolerance thresholds (varying with time), and this was linked to physical proximity and local concern. Other interviewees noted the importance of individual interests in a small community:

> *It's a very small community so you have links all over the place, and somebody with family and property and mining interests, economic interests then in the position of chief minister can leave you in a very difficult position.*
>
> [Senior scientist MVO]

The implication of this is that the scientist was aware of economic factors that might affect decision-making in the NDPRAC. This is similar to the reference to "independence" in the previous quotation: there is an implication that social and economic factors affect the level of risk tolerated by members of the governments.

> *If they react too soon they'll be accused of causing economic ruin... you're taking away people's homes and means of sustaining themselves. You take the homes of the few wealthy down there, then you take away the jobs of the gardeners and the cleaners and in a small economy you're starting to cause ripples. It's the big lives versus livelihoods issue that you've always got with a volcano.*
>
> [Senior scientist MVO]

Many of these quotations express an awareness of the social dynamics that were affected by the land-use decisions, and the potential for accusations to be made against the NDPRAC for overreacting. This reality was closely linked to frustration about attitudes towards the volcano observatory during evacuations:

Now, when you actually have to tell the authorities that you think this place is not safe, that the authorities will actually evacuate people ... and can hide behind the MVO regarding the actual decision, ...if we evacuate you it's not for the sake of it, it's literally that you're actually in danger... I can't think of any evacuations which were not fully justified, here, and but they have this kind of sentiment that the MVO's behind all this.

[Senior scientist MVO]

The tendency for scientists to be blamed for unpopular decisions demonstrated the pressure that was felt in the assessment process.

What almost always happened is that people didn't know who to blame – anything to do with the volcano, they would then tend to blame MVO... I think this is a well known strategy in Montserrat. I think that a lot of the government people and the chief minister – all sorts of people do it ... But it's something that I think we're all familiar with and used to dealing with. I think that's almost business as usual.

[Senior scientist MVO]

An undercurrent in these quotations is the disjunction between a "low" risk in probabilistic terms, and the felt "reality" of the risk. This uncertainty was identified as a source of the frustrating encounters with the small population that resisted evacuation. Scientists and officials maintained that the evacuations had always been necessary. Local people in general agreed, but some felt that since the houses in question had not been destroyed, the evacuations were "false": there is a distinction between local and scientific understanding of decision-making under uncertainty.

There was also some distinction between SAC scientists and MVO scientists in this context – MVO scientists were much more conscious of the direct impacts of decisions on attitudes to the observatory. They were living on the island and therefore had to interact with members of the public on a daily basis (compare Rothstein et al., 2006). There was a recognised need to try to delineate the scientific work and keep it separate from the decision, but also an awareness that the two are closely linked in the perception of everyone else: even if the process of risk assessment is distinct from the decision-making, there is clearly dialogue between them through human language and interaction. The period covered in this paper – January to April 2007 – was also characterised by a much greater involvement of the SAC than was standard in the longer term. In general, SAC assessments were six-monthly. There was a confessed blurring of the roles between the MVO and the SAC at this point, partly because the SAC had the modelling expertise, partly because of legal issues and partly because political pressure was high. Boundary work was ongoing both between science and policy, and within the science.

Models and experts

An important question in the context of scientific advice is the cognitive influence of models on experts, particularly if the models represent more than the "standard way of doing things". The significance of the models may be exaggerated, for example, by those close to them and involved in their development (e.g. Shackley and Wynne, 1996) – or such an exaggeration may be perceived by the public.[4] Yet withholding new scientific results from a risk assessment or a published risk map could easily be interpreted as negligent should a foreseen event occur. The disclosure of information is clearly an imperative for good scientific risk governance; the challenge is ensuring that the models are understood more widely as models and not as watertight predictions. An example was provided by a senior scientist (SAC):

Is it capable of a big Plinian eruption that would threaten the north? We think No. The last time we looked at it was about 18 months ago . . . there's no real new information since then. The only information there is going to be will either be new stratigraphy/petrology information that comes along, or it could be some new whizzo model that predicts giant Plinians 15 years after the start of a new system like this, which seems unlikely.

This question pervades risk assessments throughout the eruption, particularly early on when there was high uncertainty about the potential for large magnitude eruptions – once knowledge became available, the risk to the north decreased. The communication of risk as it is increased or decreased by scientific knowledge expansion raises questions about the nature of risk and uncertainty. An increase in knowledge can legitimately increase the risk, while reducing the (epistemic) uncertainty. Interpretation of the results requires judgement, as does any probabilistic assessment based on them: the models demonstrated what might happen if a particular volume of rock was involved in a blast, but not the likelihood of it happening (or the likelihood of the model being accurate). This was assessed using elicitation and Monte Carlo population impact modelling (Wadge and Aspinall, 2014).

The use of models and elicitation – with high uncertainties – as socially authoritative guidelines was not universally accepted, either by the public or by the scientists, though many appreciated that it was necessary.[5] Unfortunately, adding uncertainties to the models in order to embody precaution in the process made the lines more conservative and therefore less likely to be well received by the public: the uncertainty bounds on either side of a best-fit model line may be applied to official zonation by selecting the line furthest from the source of the hazard. This is a subjective administrative decision, but one that appeals under high uncertainty. Trying to communicate the idea of model uncertainty proved very difficult – not least because the nature of scientific models in general may be poorly understood by non-scientists.

I remember back to one SAC report when somebody said, "Oh, there's a danger of a lateral blast and it's going to be so many per-cent probability that it would happen", and it was a very high probability, and to this day it's never happened, so people would question that and ask why. And they'd say, "Oh, we modelled it", and some people said, "well you only get out of your computer what you put in", so you know I think perhaps there's room for people to discuss that. . . What else has been modelled in the world? What modelling has been shown to be successful? Things like that.

[Local official]

The perception by some residents that the scientists were somehow deliberately seeking to produce models that indicated high risks is revealing. It suggests that the scientists' awareness of some hostility locally was accurate, and that some local people were not clearly able to separate scientific modelling from political decisionmaking with political motives. Other interviewees varied in their responses to seeing the models at a public meeting. Some were sceptical, as the quotation above shows, while others were

[4] This was suggested by non-scientist interviewees.

[5] There were no obvious patterns in the demographic of those who expressed scepticism.

convinced and declared that the models had made them appreciate the risk more fully. There were no significant demographic indicators of their views. However, from the point of view of the authorities, accrediting the decisions to "scientific models" was very appealing – and this is comparable to recent discussions concerning social authority (as opposed to epistemic authority) of climate models (Hulme and Mahony, 2010; see also Shackley et al., 1998; Shackley and Wynne, 1996; Demeritt et al., 2010). Ultimately, the management and measuring of risk as science evolves and new tools become available requires a complex set of social and scientific judgements by those carrying out the risk assessment. Thus, while models can bring some order to the boundary between scientific advice and policy making, they also raise challenges on both sides.

In April 2007, the dome stopped growing. A further interim assessment was carried out in July 2007, and people were allowed to return to their homes in the Lower Belham Valley. Donovan et al. (2012a) described the hazard level system that was developed on Montserrat in 2008. Prior to 2008, several different zonation and alert level systems had been used, including a microzonation system in 1997 and a series of risk maps from 1997 to 2006 (Aspinall et al., 2002; Haynes et al., 2007). In February 2006, an alert level system was devised by the MVO, and the government assigned particular civil actions to each level of the system. In October 2007, the SAC noted in their report that these actions were insufficiently flexible given the nature of volcanic activity. Following this, the new MVO management instituted a new "Hazard Level System" in August 2008, which combined scientific modelling as discussed in this article with a level of flexibility in the actions required by each hazard level (from 1 to 5). In designing the new system, models were used to draw the lines, but aerial photographs were used within the model uncertainty to decide which houses should be in each zone. The demonstration of flexibility, albeit small, in the boundaries and in the civil actions was appreciated by local people, who felt that their concerns about the previous system had been heard. While models themselves are "boundary-ordering devices", which evolve with time and may provoke small shifts in the boundaries, the HLS itself is a boundary object that has been shown to be very effective (Donovan et al., 2012a). It is also the result of a long period of scientific endeavour to refine the models, and scientific and political will to find a flexible system.

Conclusions

The case study in this article shows the profound social and political challenges that face science as it is applied in risk management – and that face policymakers as they seek to order the natural landscape and make it 'safe'. It shows that scientific advancement is both triggered by and feeds into the decision-making process. Scientists on Montserrat were simultaneously focussed on explicitly scientific endeavour (e.g. modelling a pyroclastic flow) and on applying belief-based probabilistic methods as boundary-ordering devices to manage uncertainty. The framing of the reports suggests that this was boundary work – seeking to uphold the validity of these methods as scientific, whilst consciously applying them to social questions and being aware of the uncertainty. Politicians, on the other hand, used the models as boundary objects that could be called upon to bring authority (from science) to their decisions. The liminal nature of this work is evidence that the "boundary" itself is incomplete, in nature and in time: dialogue between scientific method and policy occurs via diffusion. Science leaks into the political, and vice versa, through a boundary-layer that is characterised by uncertainty and fluidity. Models are used to bring some order to the boundary, but are themselves ambiguous: they can be applied to the negotiation of authority and uncertainty in different ways by different groups.

The use of a suite of models with different physical bases on Montserrat shows an awareness of their individual limitations as representations of the natural system and provides a way of incorporating the resulting uncertainty into the assessment. However, the models did not always have an ordering effect because they were open to challenge from stakeholders, because of their social and political impact on evacuation zones and because some of the people recognised that the models had a human origin ("you get out of your computer what you put in!"). This is similar to the "institutional risk" described by Rothstein et al. (2006): in the process of doing scientific risk assessment, institutions take a risk that their assessments may not be well received. Where multiple institutions are involved, that risk may not be evenly spread – for example, the setting of boundaries was done by the NDPRAC on the basis of modelling by the SAC, but both the SAC and the MVO perceived some consequences. The ways in which the decisions were justified to minimise institutional risk to the government was perceived as laying the "blame" on the scientists, even though the uncertainty was very high. Lines on maps are more obvious to a lay reader than the uncertainties in the tables of a risk assessment: there is an imbalance between the scientific perspective and the social interpretation. In the case of Montserrat, this is complicated by the multiplicity of groups, nations, laws, institutions and interests that are represented on and around a small island. The lines on the maps were clearly viewed as occupying different spaces and differently-certain spaces by different actors. Furthermore, the murky line between science and policy was placed differently by different actors. These positions were connected through flows of, among other things, responsibility, blame, ownership, uncertainty and identity. Models provided a means of ordering the potential claims made about the lines.

The representational power of models can thus increase their authority but unintentionally hide the uncertainty inherent in them. The uncertainty may be clear to those with "inside" knowledge, but has to be framed externally to the models themselves (such as in reports). Philosophers of science have distinguished between "internal" and "external" modes of science (e.g. Shapin, 1992). Boundary-ordering – of which risk assessment is typically an example – occurs on the threshold, neither fully inside the scientific community nor outside it. The transdisciplinarity of risk undermines a purely quantitative assessment: it is socially contestable because it is socially constructed: while science may resist accusations of social construction, risk and hazard cannot. Qualitative uncertainty and ambiguity may stem from the nature of the assessments themselves, their social context and the differing perceptions of uncertainty that they try to order (Stirling, 2007). Narratives provide a means of expressing the complex relationships between people, ideas and objects in the risk management process – they can describe and elucidate connections. Studies of the process of science in such contexts are critical, since the dynamic nature of science through space and time (Massey, 1999) causes shifts in uncertainties, as occurred during 2007 on Montserrat. The role of social uncertainties – such as those from scientists' own individual approaches and judgements – suggests approaches that tend towards "scientific perspectivism" (Giere, 2004) rather than clinging to positivism or seeking to convince scientists to accept pure social construction. However, these types of approach depend upon a reflexive acceptance of the role of the researcher (or modeller) in the generation of the models.

Uncertainties – both scientific and social – produce a boundary layer in which diffusion is possible between scientific advice and policymaking. While disaster risk reduction has tended to focus on the social processes within populations that affect risk, there is a rich field in studying the social processes of science as it informs policy as well and in thinking about how these processes might be accounted for. This article suggests that as well as promoting the integration of local and scientific knowledges (Gaillard, 2008; Gaillard and Mercer, 2013), it is necessary to reconceptualise the science–policy interface and its impact on and through scientific subjects in the management of disasters: it is a diffusive, open space with multiple connectivities.

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