Reflections on the communication of uncertainty: developing decision-relevant information

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ABSTRACT

Successful emergency management decision-making during natural hazard events is fundamentally dependent upon individual and team situation awareness (SA, i.e., how selection, interpretation, and understanding of available information defines the problem and identifies solutions) whilst operating under high time and risk pressures. The development and evolution of SA, and response effectiveness during a crisis, depends upon information and advice from external experts. This advice is characterised by stochastic (system variability) and epistemic (lack of knowledge) uncertainty, constraining decision-making and blocking or delaying action. How this uncertainty is communicated, and managed, varies throughout the phases of emergency management. Through this 'Insight' paper, we review how people cope with uncertainty, individual and team factors that affect uncertainty communication, and inter-agency methods to enhance communication. We propose communicators move from a one-way dissemination of advice, towards two-way and participatory approaches that identify decision-relevant uncertainty and data information needs pre-event, identify what communication efforts should focus on during a crisis, and thus enhance situation awareness and data sharing.

Keywords

Uncertainty, decision-relevance, science advice, participatory, co-production.

1. INTRODUCTION

Throughout the response and recovery to a natural hazard event, it is vital that the multiple agencies involved in the response have effective communication processes and protocols to enhance the sharing of data and information, and to respond and recover effectively. We will argue that effective communication within event is fundamentally dependent upon successful pre-event activities that enhance individual and team understanding of each other's needs, responsibilities, and roles, such that communicated data and information can meet the needs of decision makers in time and space (Borodzicz and van Haperen 2002, Cannon-Bowers and Bell 1997, Crego and Harris 2002, Endsley 1997, Martin et al. 1997, Owen et al. 2013, Paton, Smith and Violanti 2000, Pliske et al. 2001). However, the presence of uncertainty can mediate and limit this process, both in terms of the technical or scientific uncertainty inherent to the data, risk assessment, or models, and due to uncertainty about the communication environment. In New Zealand, a number of significant recent natural hazard events have highlighted the need to identify how best to communicate scientific and technical uncertainty to enhance stakeholder and individual decision making, before, during, and after a crisis (e.g. Becker et al. 2015, Jolly and

Cronin 2014, Wein et al. 2016). This includes identifying how best to communicate scientific, technical, data, and information uncertainty (e.g. in model representation, model and parameter choice), and how to manage the uncertainty in the communication environment (e.g., missing, ambiguous, contradictory information arriving in rapidly evolving situations). To achieve this, we first need to understand how a range of stakeholders react to, conceptualise, and cope with uncertainty, as well as their decision uncertainty needs... This includes information and decision management systems being designed to accommodate how different stakeholder groups have different information needs and interpret information in diverse ways while functioning in the context of a given event.

In this 'Insight' paper, we reflect upon key issues from the recent literature on uncertainty, as a basis for outlining our recommendation for a move towards more participatory approaches to the identification and communication of data uncertainty. We first outline the nature of uncertainty (section 1.1) by briefly reviewing the wide range of 'uncertainties' that exist in a natural hazard multi-agency response, ranging from uncertainties in behaviours through to the many layers of uncertainty in the information. This is followed in section 2 with a brief review of how people cope with uncertainty via different decision-making processes (section 2), and the role of mental models in those processes (section 2.1), summarizing how the development of effective shared mental models can improve situational awareness and reduce communication uncertainties. We also highlight how an individual's mental model affects their interpretation of scientific communications, and how their 'model of science' thus impacts their understanding of scientific uncertainty. We then briefly discuss the different languages used to describe uncertainty (section 3), and processes that can be adopted to help identify and categorise uncertainty as well as reduce the 'linguistic uncertainty' inherent to the language we use to describe our data. Finally, in section 4, we review additional lessons from a recent systematic literature review which focused on the particularly challenging issue of communicating the technical uncertainty inherent to numerical and risk modelling (Doyle et al. 2018). This review identified several key thematic areas in the literature that provide lessons for effective uncertainty communication. We reflect here on three of these themes: the role of different epistemologies and disciplinary cultures (section 4.1), the role of trust (section 4.2), and the role of participatory approaches pre-event to enhance communication (section 4.3). We focus on these due to the important role they play in enhancing inter-, and intra-, team situational awareness, and the role they play in improving the understanding of scientist's and decision-maker's needs, capabilities and resources, all of which contribute to more effective data sharing. In section 5, we conclude that such participatory approaches can help identify decision-relevant information, and thus contribute to the development of effective communication protocols ahead of events. Developing such competencies pre-event thus enhances multi-agency response communications in-event (see Doyle and Paton 2017, Owen et al. 2013). Communicators must move from a one-way dissemination of advice and uncertainty, towards these two-way and participatory approaches that seek to identify the decision-relevant information and uncertainties, and seeks to focus communication efforts upon those needs. This is particularly important in contexts where information needs and uses evolve over time.

1.1 The nature of uncertainty: in actions, in information.

The effective management of complex emergencies is an activity that transcends the capability of any one organization or agency. This makes inter-agency communication an important component of an effective response. Complicating factors in this context include a need to understand how the nature, quality and utility of inter-agency communication is affected by agencies having different roles. Thus information and decision needs, and the fact that all agencies need to manage evolving events. This is further complicated by event characteristics and implications which change over time in an overarching climate of uncertainty. The latter point introduces a need to understand uncertainty and its implications. This itself is a challenging activity as uncertainty is not a homogenous construct.

Considering uncertainty at the individual level, Kuhlthau (1993, as cited in Sonnenwald and Pierce 2000, p. 463) consider uncertainty to be a cognitive state that causes anxiety and stress. While this is an accurate description of the experience for many in everyday life, it is less applicable for emergency management professionals. Rather than imposing constraints on thinking and action, when experienced by trained personnel, anxiety and stress can actually facilitate and empower action (Flin 1996, Paton and Flin 1999, Paton and McClure 2013) and act as a motivational force (Smithson, 2008). For crisis decision makers, recognition of the latter leads to a need to focus more on situational uncertainty. In this context, Lipshitz and Strauss (1997, p. 150) define uncertainty as "a sense of doubt that blocks or delays action", that can be "classified according to the issue (i.e., what the decision maker is uncertain about) and source (i.e., what causes this uncertainty)." Sources include a) "incomplete information", b) "inadequate understanding", and c) "undifferentiated alternatives". Schmitt & Klein (1996, as cited in Klein 1998) add to this list and discuss how sources of uncertainty can emanate from 1) missing information; 2) unreliable information; 3) ambiguous or conflicting information; or 4) complex information. These uncertainties can occur on the level of the data, the level of knowledge, and people's level of understanding (Klein 1998) (see review in Doyle et al. 2018).

Even when having motivating qualities, situational uncertainty introduces delays in action for several reasons, including decision makers being unable to a) judge if the situation is typical; b) prioritize relevant cues to inform the decision; c) form expectancies; d) develop a vision for plausible goals; and e) being uncertain regarding which action to take. Each of these contributes in different ways to discomfort, fear and doubt (Klein 1998, p. 278). If these exceed the capacity (training, experience etc.) of the decision maker, decisions may not be made, or if made, may not be enacted in timely and effective ways (Paton and Flin 1999). However, given that these are inevitable consequences of working on mass emergency and disaster settings, it becomes important to understand how such conditions can affect performance and to use the knowledge of those disaster-setting characteristics to inform the development of capability. The use of simulations that develop both situational understanding and stress and coping capability are especially valuable in this context (Paton and Flin, 1999). It is also important to appreciate that inter-agency work contributes additional kinds and sources of uncertainties (that vary from one stakeholder to another), and thus how uncertainty needs to be managed within the inter-agency context.

For example, uncertainty affects both the scientific advisors in their decisions regarding communication, as well as the decisions made by the emergency managers that depend upon the advice they receive from scientific advisors. Hence, it becomes important to appreciate the cascading properties of uncertainty as these can be magnified through sequential and iterative information search, evaluation and decision processes. A significant contribution to this derives from the fact that uncertainty in the source (and interpretation) of information varies between these groups. For instance, advisors deal with uncertainty in their assessments of hazard processes and predictions of future activity, whereas emergency managers face uncertainty in applying data with implicit uncertainty to complex response management settings (e.g., regarding where to deploy resources, and knowing that decisions change their future options as resources cannot readily be committed to other locations) (Paton and McClure 2013). Uncertainty related to communication and information is thus both a source of uncertainty itself as to what to communicate, as well as having sources of uncertainty within it, and being a cause of future uncertainty (as reviewed in Doyle et al. 2018). Uncertainties can also arise between advisors and managers from differences due to: a) discipline and training (including the degree to which processes such as cross training has been part of inter-agency team development), and b) how they relate to their roles and responsibilities (e.g., those from bureaucratic agencies tend to become more rigid in their adherence to rules and procedures when crises occur). These differences, and their different frames of reference, their different information management and processing approaches, and the application of different mental models of their situation (discussed further in section 2.1), all act to create further uncertainties that must be understood and managed (Paton and McClure 2013).

Science advice about natural hazards is often 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). Uncertainty has not always been given the prominence in conceptualising information and decision management (both within agencies/discipline and between them) it deserves. The value of elevating its importance has being reinforced by, for example, Becker et al. (2015) and Wein et al. (2016) calling for the understanding of the diverse, evolving and specific decision-making needs of scientific information that emerged in information users after the Christchurch earthquake sequence. This paper seeks to redress this imbalance. It follows from the above discussion that to assist in effective decision making under uncertainty, communicators should first understand "the various dimensions of uncertainty [to help] in identifying, articulating, and prioritising critical uncertainties, which is a crucial step to more adequate acknowledgment and treatment of uncertainty in decision support endeavours" (Walker et al. 2003, p. 5). To encompass these issues, this paper adopts the term "uncertainty communication" to describe its area of interest.

2 Coping with Uncertainty: Decision making, mental models and inter-agency communication

As discussed by Patt (2009) a particularly challenging issue for uncertainty communications is the wide range of uncertainty decision making models that exist, including economic, psychological and political models. It is beyond our scope to review all these here, but focusing on the psychological literature (see reviews in Doyle, McClure, Paton, et al. 2014, Doyle and Paton 2017), the theory of two "parallel processing systems" (Chaiken and Trope 1999, Epstein 1994, Sloman 1996, Slovic et al. 2004) describe the decision making processes that occur at an individual level. Type 1 is an *affective* process involving rapid, unconscious, action-oriented processing, where people interpret risk as an emotional state or feeling (e.g., fear, dread, anxiety; Doyle, McClure, Paton, et al. 2014, Epstein 1994, Loewenstein et al. 2001, Slovic et al. 2004, Smithson 2008). This can be "intervened by distinctive higher order" Type 2 processes (Evans and Stanovich 2013a), or *analytical* processing systems (Epstein 1994), which utilise hypothetical thinking, and more deliberate computational cognitive processes by using rules to analyse the data and justify actions. Decisions made in a crisis can involve a complex balancing act between these two processes, influenced by the degree of uncertainty or threat and an individual's roles, responsibilities and training (Doyle, McClure, Paton, et al. 2014, Evans and Stanovich 2013a, b, Keren 2013, Keren and Schul 2009, Kruglanski and Gigerenzer 2011, Loewenstein et al. 2001, Osman 2013, Thompson 2013).

Emergency response conditions are characterised by ill-structured problems; uncertain dynamic environments; shifting, ill-defined, contradictory or competing goals; action/feedback loops; time stress; high stakes; multiple players; and influences from organizational goals and norms (Crichton and Flin 2001, Doyle and Johnston 2011, Klein 2008, Zsambok 1997). These are not 'ideal' for Type 2 processing (Flin 1996, p. 141–142, Saaty 2008). Instead 'naturalistic' decision making processes have been identified as being able to go some way towards facilitating functional decision making in such dynamic settings (Crego and Spinks 1997, Crichton and Flin 2002, Pascual and Henderson 1997). These include 1) recognition primed and intuition led action; 2) action based on procedures; 3) analytical comparison of options; and 4) creative designing of a novel course of action. A decision maker can move through this spectrum (ordered in terms of decreasing pressure and increasing time), depending on the task and specific demands that present at a particular stage in events characterized by evolving conditions (Doyle and Johnston 2011, Martin et al. 1997, p. 283), as well as a responder's strategic analytic or tactical coordinating response level and decision needs (Paton et al. 1998, 1999, Paton and Flin 1999).

Because they inevitably involve inter-agency and inter-disciplinary collaboration, these processes depend fundamentally upon individual and team Situation Awareness (SA; Endsley 1997, Martin et al. 1997). Situational awareness encompasses 1) the perception of the problem elements in time and space; 2) the comprehension of the current situation (in relation to agency/team goals) and 3) the projection of the future status. The development of effective SA, and the projection of future status, is particularly important when considering uncertainty, as uncertainty often evolves and grows in to the future, especially in emergency management situations. Thus, the soliciting of advice and opinions of experts is often a vital part of these decision processes. This may be enhanced by the development of communication protocols and techniques to identify decision information needs ahead of time, with a particular focus on identifying which uncertainties will have the greatest impact upon those decisions (discussed further in section 4.3).

Lipshitz & Strauss (1997, p. 160) found that decision makers "Reduce, Acknowledge or Suppress uncertainty depending on its nature or quality". However, this assumes a 'rational' or analytical decision maker, and does not incorporate the uncertainties introduced by individual interpretative processes, biases and interactions, or the role of more implicit or experiential modes of thinking (Epstein 1994). As discussed by Eiser et al. (2012), there is a need to move beyond 'rational choice' models in natural hazards, and consider how people's interpretations of risk reflect their experience, feelings and bias. This is supported by the research of Doyle et al. (2014) and McClure et al. (2014), who discussed how people's interpretations of forecast likelihood statements were found to be not 'rational' as they are influenced by prior experience and knowledge of phenomena as well as cognitive biases. This line of inquiry makes it pertinent to consider how to capture these socio-psychological processes and how they inform understanding of uncertainty communication and its functional implications. One way of doing so is via the construct of mental models.

2.1 Mental models

Effective inter-agency and intra-team communication depends upon a good shared mental model, particularly when high levels of uncertainty about evolving events exist (Doyle et al. 2018, Paton and McClure 2013). A mental model describes how someone understands an issue, any dependencies, and causal beliefs (Bostrom et al. 2008), and how they impose meaning on uncertain and unpredictable events to make decisions (Paton and McClure 2013). They can include a mental 'map' of a response operating environment (Flin 1996, Paton and Jackson 2002, Rogalski and Samurçay 1993), with such maps encompassing the needs, responsibilities, roles, dependencies and demands of other members of the response. They can also encompass an individual's prioritisation of different information and weighting of hazard attributes upon their management of risk; including socio-political and economic criteria and demands (Paton and McClure 2013). An effective shared mental model reduces the uncertainty about what to communicate, as a decision maker's needs are anticipated and understood, through a shared understanding of the task at hand (Lipshitz et al. 2001, Orasanu 1994, Pollock et al. 2003, Salas et al. 1994). What this entails is depicted in Figures 1 and 2.

As illustrated in Figure 1(a), a wide range of mental models can exist, including those about the hazard, the communication network, and an individual's or organisation's responsibilities and needs, and so on. These mental models affect the interpretation of information, which can also be mediated by several other cognitive, social, psychological, environmental, and experiential factors (such as those illustrated in Figure 2). In the absence of effective cross training or team development, the situation depicted in Figure 1 (b) prevails. People function in adjacent roles, but each brings their own content (from Figure 1(a)) to the role. Hence there is no coherence or inter-agency/disciplinary functioning. This poor shared mental model can result in uncertainties not just in what to communicate, but also how and who to communicate too, and often requires explicit requests for information in response (Crichton and Flin 2002, Klein 1997, Paton and Jackson 2002), The goal of activities such as cross training or team building is to create the relationships depicted in Figure 1(c), where each agency representative has their own role to play, but (as depicted by the overlap), they do so in a more coherent way and one that creates a "whole is greater than the sum of its parts" approach to functional response. This has several practical implications. A good shared mental model enhances levels of understanding, creating an environment for more effective data and information sharing, and improving situational awareness by increasing understanding of each other needs in both time and space (Endsley 1997, Martin et al. 1997).

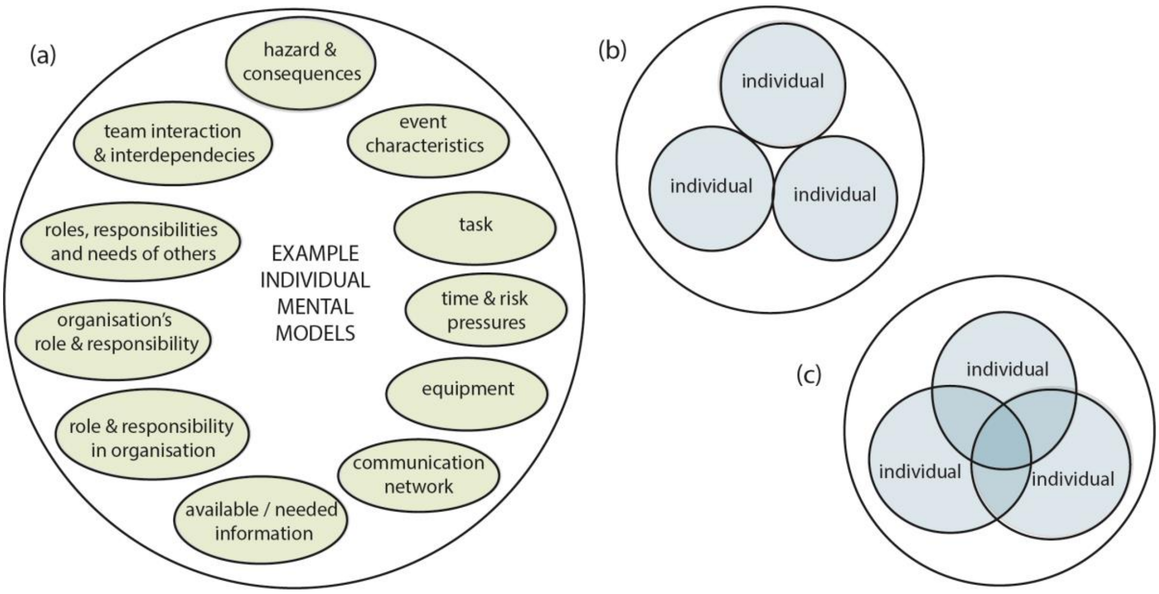

Figure 1: a) Examples of the various mental models within an individual's over-arching or super-ordinate mental model during a volcanic crisis. b) A poor shared mental model between individuals. C) A good shared mental model (Doyle and Paton 2017).

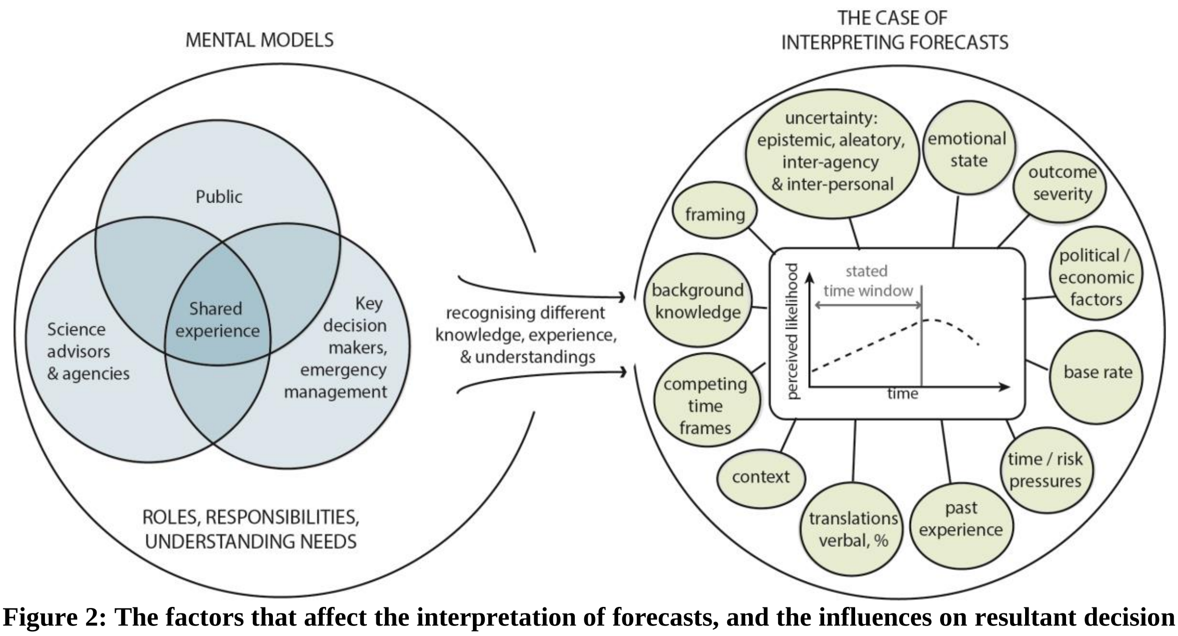

Figure 2: The factors that affect the interpretation of forecasts, and the influences on resultant decision making (Doyle, McClure, Paton, et al. 2014).

Effective communication occurs when an individual continues to use their 'expert' mental models in complement with the over-arching or superordinate mental model. They then integrate their individual mental models of their role, how they relate to others within their organization, and how their organisation fits within the wider response (Doyle and Paton 2017, Owen et al. 2013). This illustrates how stakeholders do not need to have identical understanding and roles. Rather they need to have shared understanding of, for example, how their respective knowledge, experience and skills complement others in ways that ensure that the emergent shared experience of an event increases the likelihood of their acting in coherent and complementary ways. A "team" whose structure reflects Figure 1(b) would function less effectively than a team whose functioning reflected a Figure 1(c) structure. Understanding this notion of coherence has further implications.

An additional level of uncertainty can arise in inter-agency communications through the mental models gulf (Morgan et al. 2001). This describes a gap between "what experts know and the plan they develop, versus what key public know and prefer" (Heath et al. 2009, p. 129), see also Doyle et al. (2014, Doyle and Paton 2017). However, if response teams (including advisors) have developed an effective shared mental model (via training and other techniques ahead of time; see section 4.3), then communication in an event can move from resource intensive explicit requests for information (Crichton and Flin 2002, Klein 1997), to implicit supply of advice as they anticipate information that others need (Kowalski-Trakofler et al. 2003, Lipshitz et al. 2001, Paton and Flin 1999). This also allows decision makers to focus on task management and reduces uncertainty around missing or requested information. As reviewed in Doyle et al. (2015) the quality of these shared mental models can be improved through both training and effective team-based simulations (Borodzicz and van Haperen 2002, Cannon-Bowers and Bell 1997, Crego and Spinks 1997, Paton, Smith and Violanti 2000, Pliske et al. 2001), as well as from the analysis of past responses. An implicit communication style dominates in effective teams (Kowalski-Trakofler et al. 2003, Lipshitz et al. 2001, Paton and Flin 1999, Paton and Jackson 2002), and in a science advice situation ensures information is useful, useable and used (Aitsi-Selmi, Blanchard, et al. 2016, Rovins et al. 2014). Advisors must recognise the specific needs of decision makers prior to an event and establish procedures to provide that information within the event's organisational structure (Doyle et al. 2015, Doyle and Paton 2017, Owen et al. 2013). This is particularly important in distributed decision making scenarios (Paton and Jackson 2002, Rogalski 1999, Rogalski and Samurçay 1993).

As reviewed in Doyle et al. (2018), when communicating information that includes uncertainty, an individual's model of the world and science affects their perceptions of the scientific uncertainty because individuals interpret information based upon their 'science model' (Maxim and Mansier 2014), as illustrated in Figure 2. For example, Budescu et al. (2012) found that interpretations of uncertain verbal statements varied depending upon ideologies and beliefs in climate change, while Tak et al. (2015) concluded that in the absence of any textual explanation of an uncertainty range, people will apply their own internal model of the uncertainty distribution. People are not just influenced by the framing of a message, but also by their prior expectation of the message (Rabinovich and Morton 2012). This also depends on whether they assume a classical model of science (which considers science to be the 'search for truth'), or a Kuhnian model of science (which considers 'science as debate') (Kuhn 1962). In the latter, actions are less likely to be undeterred by uncertainty, and uncertainty may actually increase motivations (Rabinovich and Morton 2012). People with a Kuhnian model of science are perceived by Rabinovich & Morton (2012) to trust a message more if it includes uncertainty as it matches their expectations. However, a classicist would distrust an uncertainty message as they search for absolutes. It is thus important to assess and adapt communications depending upon audience beliefs (see section 4.1 and Doyle et al. 2018). Similarly we can seek to understand how individuals adapt and create opportunities to function in uncertain and dynamic conditions, and how they rationalise their experience through different frames of reference and their social models, via the fields of social constructionism and symbolic interactionism (Burr 1995, Falkheimer and Heide 2006, Griffin 2006), where "crisis communication is understood and analyzed as a sense-making process (e.g. Weick, 1979) where reality is negotiated and constructed in cultural contexts and situations, rather than distributed from a sender to a recipient" (Falkheimer and Heide 2006, p. 180)

3 THE LANGUAGE OF UNCERTAINTY: TYPOLOGIES AND LINGUISTIC UNCERTAINTY

Klein (1998, p. 277) highlight that when uncertainty is discussed the language used is often muddled, being discussed in terms of "risks, probabilities, confidence, ambiguity, inconsistency, instability, confusions, and complexity", including uncertainty about 'future states, the nature of the situation, the consequences of action, and preferences'. Doyle et al. (2018) highlight the wide range of schemes that exist in the literature to define and classify uncertainties (Bammer et al. 2008, Bjerga et al. 2012, Blind and Refsgaard 2007, Daipha 2012, Grubler et al. 2015, Handmer 2008, Janssen et al. 2005, Kloprogge et al. 2011, Kwakkel et al. 2010, van der Sluijs et al. 2011, Smithson et al. 2008, Stirling 2010, Walker et al. 2003). For example, Walker et al. (2003, p. 8) developed a typology for uncertainty management in model-based decision support, which considers three overarching categories: First, 1) the *location* of the uncertainty encompassing: a) the context of the model, b) the model uncertainty, c) input variables uncertainty, d) parameter uncertainty, and e) accumulated model outcome uncertainty. Next, 2) The *level* of uncertainty, which considers where the uncertainty sits along a scale from determinism, statistical uncertainty, scenario uncertainty, recognised ignorance, indeterminacy, through to total ignorance. Finally, 3) the *nature* of the uncertainty: whether it is epistemic and due to knowledge imperfection, or whether it is a variability uncertainty (or ontological uncertainty) due to behavioural variability (micro), social variability (micro and macro) and natural randomness.

A key element of the relationship-development processes depicted in Figure 2 is the opportunity for stakeholders to familiarize themselves with sources of uncertainty from others, and to take steps to explore strategies to reduce it or accommodate it in their own planning and operations. For example, if communicators clearly identify and define all types of uncertainty in technical science (Adler and Hirsch Hadorn 2014, Aven and Renn 2015), they can 'avoid misinterpretations of uncertainty characterizations' (Adler and Hirsch Hadorn 2014, p. 668) and provide advice that is more rigorous, robust and 'democratically accountable' (Stirling 2010, p. 1029). As reviewed in Doyle et al (2018), this is particularly important for model uncertainties as larger 'deep' uncertainties can form due to the interdependences between model assumptions and relationships (Walker et al. 2003). However, to communicate all uncertainties present can overwhelm a message and decision, as providing as much advice as possible can hinder the decision process due to cognitive overload and an overuse of available resources (Eppler and Mengis 2004, Omodei et al. 2005, Quarantelli 1997, Schraagen and van de Ven 2011). Thus, it is important to classify and identify the uncertainties present, such that those most relevant and important to the decisions can be identified and be the focus of communication efforts, and such that stakeholders can accommodate this in their own planning and operations.

Such typology and classification schemes are fundamentally dependent upon a shared understanding of the definitions and words to reduce linguistic uncertainty (Elith et al. 2002, Griethe and Schumann 2005, Grubler et al. 2015, Kloprogge et al. 2007, Leyk et al. 2005, Moss 2011, Van Steenbergen et al. 2012). Shared classification schemes and prioritization of uncertainties can be developed through participatory and engagement techniques ahead of time, discussed in section 4.3. Any standardisation of the language and methods used to represent and communicate uncertainty, must remember organizational, disciplinary, context, and individual differences in understanding that will affect the appropriate terminology to use (Briggs et al. 2012, Budescu et al. 2009, Han 2013, Mastrandrea and Field 2010, Moss and Schneider 2000, Patt and Dessai 2005). This is discussed further in section 4.1.

Beyond the appropriate classification schemes for uncertainty, and the linguistic uncertainty regarding the classification terms between disciplines, issues also arise regarding the perceptions of the language used to communicate uncertainty, such as probabilities, both at an individual and discipline level (Doyle, McClure, Johnston, et al. 2014, Paton and McClure 2013). For example, it has become increasingly popular to use probability statements in volcanic crisis communications (Doyle, McClure, Johnston, et al. 2014), which involve knowledge of both the dynamical phenomena and the uncertainties involved (Sparks 2003). These probabilistic statements, whether in numeric or linguistic formats, can be misinterpreted due to their framing (e.g., discipline or decision making goals etc.), directionality (increasing or decreasing, etc.) and probabilistic format (numbers or words, time frames used, etc.). This can bias people's understanding, thereby affecting people's action choices (Barclay et al. 2008, Budescu et al. 2009, Cronin 2008, Doyle, McClure, Johnston, et al. 2014, Doyle, McClure, Paton, et al. 2014, Haynes et al. 2008, Honda and Yamagishi 2006, Joslyn et al. 2009, Karelitz and Budescu 2004, Lipkus 2010, McGuire et al. 2009, Solana et al. 2008, Teigen and Brun 1999). For example, Doyle et al. (2014), found that by simply changing a forecast statement from a "chance of an eruption *in* the next 10 years" to "*within* the next 10 years" significantly affected participants' perceptions of when in that time window an event was likely to occur. In addition, Doyle et al. (2011a) found that scientists and non-scientists differ in translations of verbal likelihood phrases into numerical equivalents, supporting the development of 'translation' schemes that consider the instinctive interpretations of the target audience, a practice now adopted by NZ's geological monitoring agency, GeoNet (Doyle and Potter 2015).

4 FURTHER LESSONS FROM THE LITERATURE

Beyond the nature, decision-making and language of uncertainty, further lessons can be drawn from the literature regarding how different perspectives of uncertainty affect inter-agency science communication. Through a recent systematic meta-synthesis literature review of 111 publications across a wide range of disciplines including psychology, policy, communication, law, climate change, health, geosciences, meteorology, risk analysis, and environmental management, Doyle et al. (2018) identified a number of themes fundamental to effective communication of model related uncertainty. This systematic review followed similar approaches to Johnson et al. (2014) which involved the 1) identification of key search terms based on questions related to communicating model uncertainty, 2) peer review of those search terms, 3) a SCOPUS database search using those terms, which returned 1,131 documents, 4) reading the abstracts of these documents and including and excluding them depending upon their relevance and scope, resulting in 85 documents, 5) inclusion of additional secondary documents of relevance found through the lead author's existing Mendeley database, PsychInfo, and other articles recommended by expert colleagues. This resulted in the final 111 documents, as fully described in Doyle et al. (2018). Unlike a traditional systematic literature review, rather than describe the characteristics and distribution of the literature (as of e.g., Connolly et al. 2012), the focus was rather to identify the key themes and emerging lessons in the literature similar to that of a meta-synthesis (as described by Cronin et al. 2008), where the literature is analysed thematically in a manner similar to qualitative data (Braun and Clarke 2006).

Through this process, the following thematic areas were identified in the 111 documents: a) the need for clear typologies to identify and communicate uncertainties, b) the need for effective engagement with users to identify which uncertainties to focus analysis and communication resources upon, c) how to manage challenging uncertainties such as ensembles, confidence, bias, consensus and dissensus, d) methods for communicating specific uncertainties, and e) the lack of evaluation of many techniques and approaches currently in use. We herein focus on the epistemology, trust, and participatory approach themes, and reflect upon these lessons for uncertainty communication. We focus on these themes here due to the fundamentally important role they play in enhancing inter-, and intra-, team situational awareness and the development of a mutual understanding of scientist's and decision maker's needs, capabilities, and resources. Which are important competencies for effective multi-agency response (as discussed in section 2; see Doyle and Paton 2017, Owen et al. 2013). In particular, pre-event participatory approaches to the generation of science data and communication protocols can improve the effectiveness of data sharing and multi-agency team situation awareness, as it can lay the basis for implicit communication styles where the scientists "recognize and understand the needs of the decision makers, [and] their timelines and thresholds" (Doyle and Paton 2017, p. 8), while encouraging shared ownership of uncertainty (as discussed in section 4.3).

4.1 Different perspectives of uncertainty: epistemologies, disciplines, and thematic contexts.

As discussed in Section 2.1, the different 'science mental models' that people hold will affect their interpretation of and action related to uncertainty (Kuhn 1962). These different science models closely relate to the different epistemic cultures (the existence of diverse ways of knowing derived from unique disciplinary histories, interests, and goals) present in different disciplines, thematic contexts, and organisations (as reviewed in Doyle et al. 2018). As described by Knorr Cetina (2013) epistemic culture describes the factors that capture the interiorized processes of knowledge creation, such as what is 'objective' and a 'true' representation of the world. It describes the set of "practices, arrangements and mechanisms bound together by necessity, affinity and historical coincidence which, in a given area of professional expertise, make up how we know what we know" (ibid, p. 4). It is important to incorporate, acknowledge, and account for different epistemic cultural differences represented by the different disciplines and professions involved in a multi-agency uncertainty classification, communication, and shared management scheme (Doyle et al. 2018, Murphy et al. 2011). Thus, the different uncertainty-decision making tolerances can be accounted for (Demeritt et al. 2007). For example, scientists will often aim to reduce epistemic uncertainty, while engineers often accept uncertainty as being core to innovation, invention, and engineering solutions (Murphy et al. 2011). Often how this uncertainty is communicated relates to the different ethical standards across disciplines such as science, engineering, law, journalism, etc. (Austin et al. 2015).

To address how to manage and communicate uncertainty, many disciplines (e.g. in climate change, meteorology, and volcanology: Gill et al. 2008, IAVCEI Subcomittee for Crisis Protocols et al. 1999, Mastrandrea and Field 2010, Moss and Schneider 2000) have established guidelines that advocate for the clear and transparent communication of uncertainty, a documentation of all processes related to uncertainty, and the use of formalised probabilistic terms and frameworks for assessment and communication. However, these approaches often do not account for the differences in how scientists and non-scientists construe the information they develop and disseminate, and how they process information (Chaiken and Trope 1999, Epstein 1994, Sloman 1996, Slovic et al. 2004). See the above discussion in section 2 on affective and analytical processes. In addition, they do not consider how non-scientist, emergency managers are being influenced by their awareness of the social, economic, and political dimensions of their decision making (e.g., the implicit need to manage response decisions with economic or political views that are imposed upon emergency managers; see review in Paton and McClure (2013)).

Experimental research has also identified how these epistemological and organizational differences influence both the perception and response to uncertain information (Budescu et al. 2012, Doyle, McClure, Johnston, et al. 2014, Doyle, McClure, Paton, et al. 2014, Maxim and Mansier 2014, Rabinovich and Morton 2012, Tak et al. 2015). For example, in an analysis of actions taken in response to a hypothetical probabilistic volcanic eruption forecast, Doyle, McClure, Paton, et al. (2014) found that scientists tended to query the scientific advice and express dissatisfaction about the quality and lack of information as reasons for not evacuating. They found that non-scientists tended to express a desire to wait for more information, while still stating their intention to start the process of preparing for evacuation. This illustrates how the scientists were reflecting their core business of data collection, while the non-scientists were reflecting their role as recipients of information and as passive planners about what could happen. In addition, even though information was very limited, more non-scientists chose evacuation compared to scientists, focusing on *actions* they would take, and *acknowledging* or *suppressing* the uncertainty in order to make their decisions (Lipshitz and Strauss 1997). Meanwhile scientists focused more on the *information* and the quality of that information, choosing to *reduce* the uncertainty in the source (information) before proceeding.

These findings highlight that a system of shared uncertainty management between scientists and decision makers both during emergency planning and analysis processes, during mitigation decisions, and in response and recovery must acknowledge and account for different discipline and organisational language and epistemological differences. In particular, Grubler et al. (2015) has found that epistemic differences can fundamentally affect the initial problem formulation, due to linguistic uncertainty and a lack of common language. In addition, different systems of scientific enquiry, ranging from analytic, empirical, synthetic, or conflictual models lead to a different emphasis in this initial problem formulation. Thus, a shared uncertainty communication and management scheme should adopt a pluralistic approach which acknowledges these differences, and then provides a basis for a more equal partnership between social and natural science (Doyle et al. 2018, Stirling 2010). Developing such a pluralistic approach depends upon an effective engagement and participatory approach between scientists and decision makers ahead of time, discussed further in section 4.3. Before discussing the concept of participatory approaches further, we first discuss the role of trust, due to its fundamental role in the maintenance and development of the relationships required for effective engagement, particularly when operating in circumstances where uncertainty prevails.

4.2 Trust

Effective multiple agency communication in a crisis is heavily dependent upon trust (see reviews in Doyle and Paton 2017, McIvor and Paton 2007, Paton et al. 2008). In environments of high uncertainty the quality of interpersonal trust is essential for collective action (Garnett and Kouzmin 2007, Pollock et al. 2003, Siegrist and Cvetkovich 2000). Trust is most important under conditions of high uncertainty, and can be further challenged when recipients in situations of high pressure, low time, and limited resources, are totally reliant on advisors with whom they may rarely interact with under normal circumstances (Doyle and Paton 2017, Haynes et al. 2007). As reviewed by Doyle and Paton (2017), it is reassuring to know that some research has shown that the communication of uncertainty can enhance the credibility and trustworthiness of the information provider (Johnson and Slovic 1995, 1998, Miles and Frewer 2003, Smithson 1999, Wiedemann et al. 2008), making the provider seem more 'honest' (Johnson 2003). However, other research has found that communicating uncertainty decreases people's trust in, and credibility of, the provider (Johnson and Slovic 1995, 1998, Miles and Frewer 2003, Smithson 1999, Wiedemann et al. 2008), enabling people to justify inaction or their own agenda, or to perceive higher or lower risks than exist. This effectively extends the discussion of epistemic culture to stakeholders outside the scientific arena. This decline in trust can reflect a lack of understanding of how the ways of knowing are derived from a unique disciplinary history, interests, and goals, and how that affects the communication process and can result in conflict and distrust due to recipients failing to appreciate that a source has different priorities and interests and capabilities. Several other factors affect whether uncertainty decreases or increases trust, including the context, the relationship between provider and receiver, and past experiences (see reviews in Doyle, McClure, Paton, et al. 2014, Doyle and Paton 2017).

Organisational cultures also influence trust. As reviewed by Doyle and Paton (2017, p. 315), scientists usually work in flatter more organic organizational cultures in which information flow is common, which makes it easier for them to share information and build trust. However, decision makers from government departments and emergency service agencies experience higher levels of hierarchical relationships and are predisposed towards maintaining their own agency-based independence (Dietz et al. 2010, Dirks and Ferrin 2001). Rivalry can thus emerge between organizations, preventing effective information sharing (Iannella and Henricksen 2007, Marcus et al. 2006, Marincioni 2007, Militello et al. 2007, Owen et al. 2013, Smircich and Smircich 2012, Waugh and Streib 2006). This further impacts the development of trust required for effective collaboration between these culturally diverse agencies (Banai and Reisel 1999, Mcknight et al. 1998, Siegrist and Cvetkovich 2000), and thus effective information sharing (Kapucu 2006, Mohr and Spekman 1994).

Agencies who only come together for the first time to collaborate in a response setting may lack trust (Dirks and Ferrin 2001). Functional collaboration, and shared experience designed to facilitate team building and shared understanding of the respective goals, needs and contributions of each stakeholder, helps to develop trust. Such pre-response activities, including training, planning and risk mitigation collaborations, and development of pre-event communication protocols and uncertainty management schemes, contribute to the development of shared mental models and enhanced functional relationships (see also section 4.3). In addition, if pre-event training is not possible, trust can be developed in-event through the concept of swift trust (Curnin et al. 2015, Faraj and Xiao 2006, Goodman and Goodman 1976, Hyllengren et al. 2011, Meyerson et al. 1996). As reviewed in Doyle and Paton (2017), swift trust develops when team members have been assigned roles that align with the response issues and the temporary work group's needs (Curnin et al. 2015). It is also more likely to emerge if members know that there is a high likelihood of future collaboration (in incident reviews, simulations), and if they identify that success relates to the super-ordinate management as much as it does to how they contribute their personal expertise (Kramer 1999).

4.3 Participatory, engagement, training, and other collaboration techniques

Throughout this review we have identified that a number of pre-event techniques for training and relationship building can enhance response by improving individual and team situational awareness, shared mental models of roles, responsibilities and needs, developing shared understanding of epistemological differences and perceptions of uncertainty, developing trust, and helping to build a mutual understanding of uncertainty management via communication protocols and the development of a common language (see reviews in Doyle and Johnston 2011, Paton and Jackson 2002). According to Kozlowski (1998, p. 120–122), team training should be considered as a sequence or series of developmental experiences that are carried out across a series of different environments, to build "knowledge and skills in an appropriate sequence across skill levels, content and target levels". Adopting a suite of training activities increases opportunities for developing an understanding of the technical issues involved and the multi-agency context in which they occur (Blickensderfer et al. 1998, Borodzicz and van Haperen 2002), and we suggest that they also provide opportunities to develop shared understanding of the relevant uncertainties, in both decisions and information (Doyle et al. 2018).

As reviewed in Doyle and Paton (2017), several training methods have been identified that can enhance naturalistic decision-making (e.g., Cannon-Bowers and Bell 1997), enhance decision skills (e.g., Pliske et al. 2001), train effective teams (e.g., Salas et al. 1997), and develop effective critical incident and team-based simulations (e.g., Crego and Spinks 1997, Flin 1996). These include cross training, positional rotation, scenario planning, collaborative exercises and simulations, shared exercise writing tasks, and 'train the trainer' type tasks, in addition to workshops, seminars and specific knowledge sharing activities (Bloom and Menefee 2014, Keough and Shanahan 2008, Marks et al. 2002, Moats et al. 2008, Paton et al. 2015, Schaafstal et al. 2001, Volpe et al. 1996). For all of these the goal is not just knowledge and skill development but to also address "how the disaster context influences performance and well-being" (Paton, Smith and Johnston 2000, p. 176). For example, scenario planning and story boarding creates multiple scenarios of "different futures" that are "credible and yet uncertain" (Keough and Shanahan 2008), in ways that accommodate the perspectives of multiple agencies. Thus response scenarios are developed that more accurately reconcile the needs, goals, and expectations of diverse agencies (Bloom and Menefee 2014, Moats et al. 2008, Paton et al. 2015). Exercises provide opportunities to practice communications, contingent planning, and enhance team mental models, as well as providing opportunities for scientific agencies to rehearse strategies to convey and include uncertainty (Doyle et al. 2011b, Doyle, McClure, Johnston, et al. 2014, Doyle, McClure, Paton, et al. 2014).

Based on the issues identified herein we consider that tools such as scenario planning can also be used as engagement techniques pre-event to help identify the science, information, data, and uncertainty response needs pre-event, and to facilitate communication of uncertainty and science for preparedness activities. For example, shared data uncertainty management approaches could draw on the methods for integrating stakeholder perspectives described by Scolobig and Lilliestam (2016). These include the multi-criteria analysis decision support method (which aims to identify the preferred solution), the plural rationality approaches (which seek compromise rather than consensus on problem formulation), or the scenario construction approaches (which aim to illustrate the impacts of different solutions).

We note that Scolobig and Lilliestam (2016) state that no approach is "better" than another (p. 1), rather "they are suited for different problems and research aims", and the choice of approach determines the type and depth of stakeholder engagement. Further approaches to developing shared uncertainty management and advice communication protocols can also be identified in the participatory, co-production, knowledge exchange, and engagement literature (e.g., Beven and Alcock 2012, Clark et al. 2016, Linnerooth-Bayer et al. 2016, Page et al. 2016, Reyers et al. 2015, Scolobig et al. 2015, Scolobig and Pelling 2016, Wall et al. 2017). As reviewed in Doyle et al 2018, a participatory approach to developing communication protocols involves "two-way communication and the relationship between scientists and policy-makers" (Patt 2009, p. 231), that prioritises giving "decision-makers enough information to know when they need to invest the time and resources to take part in a participatory process, and when they do not" (Patt 2009, p. 246). Adopting a participatory approach can help make science information more credible and legitimate (Patt and Dessai 2005), by moving away from a style where communications are formatted to meet a specific model of stakeholder decision making, which vary considerably (Patt 2009), and towards an approach where the decision makers themselves identify which science and uncertainties are important for their needs. Using tools such as scenario planning in this process can further help decision makers identify with scientists what decisions will be impacted by the uncertainties present, and through this identify the decision relevant information and uncertainty that communication efforts should focus upon (Scolobig and Lilliestam 2016).

Participatory approaches to identifying user-science uncertainty priorities, and a shared scheme for the communication and management of uncertainty are also advocated for by Faulkner et al. (2007), Janssen et al. (2005), and Beven et al. (2015). For example, Faulkner et al. (2007) outline a process to develop a classification of uncertainty in flood risk management, which focuses on a 'translational discourse' to communicate and manage uncertainty which "incorporates a conversation that maximizes the facilitation of the decision-making process" (ibid, p. 698). Through this, they move away from the traditional 'one-way' communication of uncertainty, where users and stakeholders have no 'ownership' of uncertainty. They also include 'purposeful translations' of the information to meet the decision-making needs (see also Faulkner et al. 2014). Such an approach thus prioritises the needs of the stakeholders in both the analysis and communication of scientific uncertainty (Fischhoff and Davis 2014), and thus depends upon a partnership model between scientists and users to help identify those decision-relevant needs.

Such communication approaches are thus closely related to the scientific co-production of knowledge (Clark et al. 2016, Page et al. 2016, Reyers et al. 2015, Scolobig and Lilliestam 2016, Scolobig and Pelling 2016, Wall et al. 2017). As described by Page et al. (2016) co-production of knowledge is a collaborative process between multiple stakeholders, including researchers and decision-makers, and incorporates three phases: co-design of the problem framing and the research design, co-development of the knowledge and the operationalization of research methods, and co-dissemination of findings. Such co-production is "important to help ensure knowledge is credible, salient and legitimate" (p. 86). However, it is not without its challenges. As outlined by Scolobig and Pelling (2016), effective science-policy co-production is a "long process" (p. S22) and new science and new policy developed in parallel does not automatically result in effective co-production. They outline how the "insulation of science from the institutional context" results in problematic separation of knowledge production and its use (p. S22). Alternatively, a shared uncertainty management scheme could draw from established knowledge exchange approaches. For example, Beven and Alcock (2012) outline an approach by the UK Natural Environment Research Council to bring academics and practitioners together to define guidelines for the incorporation of risk and uncertainty in assessments.

These various approaches to assessing decision makers needs for science generation and communication can be considered 'pluralistic' in the sense that they recognise the conditional nature of knowledge and different priorities and perspectives (Demeritt et al. 2007, Morgan et al. 2001, Murphy et al. 2011), and "enhances stakeholder deliberation by respecting legitimate differences in values and worldviews" (Linnerooth-Bayer et al. 2016, p. S69). As stated by Sword-Daniels et al. (2018, p. 298) "community-based disaster risk management and other participatory approaches provide mechanisms by which to incorporate this plurality of perspectives into the co-production of knowledge" (see also Williams and Dunn 2003; Cronin et al. 2004; Gaillard 2006; Cadag and Gaillard 2014). They highlight that joint fact-finding techniques can be employed to help groups create a shared vision and inform collective decision-making, even in situations with high degrees of uncertainty (Karl et al. 2007, Schenk 2016).

This approach to uncertain problems is closely related to that of post-normal science (Funtowicz and Ravetz 1993, 1999, Janssen et al. 2005, Maxim and Mansier 2014, van der Sluijs et al. 2011) which acknowledges that 'facts are uncertain, values are in dispute, the stakes are high and decisions urgent' (Funtowicz and Ravetz 1993, p. 744). As reviewed in Doyle et al. (2018), such an approach is reflective, and moves beyond just the quantitative tools inherent to uncertainty analysis (e.g. sensitivity analysis or Monte-Carlo type simulations) to include technical, methodological, epistemological and societal dimensions of uncertainty (van der Sluijs et al. 2011) and the value-ladenness of assumptions in a risk or model assessment (Kloprogge et al. 2011). A post-normal science approach recognizes that risks are interpreted and managed subjectively, proposing problem-solving frameworks that account for this plurality of perspectives (see also Krauss et al. 2012), and can encompass the 'social history of uncertainty' to solicit social science expertise in communications (Moss 2011, Patt 2007).

A pluralistic participatory approach acknowledges that people are not being irrational when they respond differently to information and uncertainty, but rather they are influenced by different individual, social, and cultural values (see also Eiser et al. 2012 and above discussion on mental models). A plural approach to communication provides a basis for more equal partnership (Stirling 2010). It requires a high level of transparency where what is communicated (in level of detail and level of quantification) depends on the needs of the decision-maker (Loucks 2002). As discussed by Aitsi-Selmi, Murray, et al. (2016), current methods for risk assessment and management are often variable and non-standardised which results in a "lack of transparency of understanding of uncertainty" (p. 11). This hampers both the communication to decision makers and their use of scientific outputs. They highlight that two-way coproduction of knowledge and participatory approaches are needed to enhance the use and application of science. We note however, as reviewed in Doyle et al. (2018), that for engagement and participatory approaches to work, it is vital that a code of practice and professional guidelines are developed for engagement, which considers funding, leadership and ethical standards (Beven et al. 2015, Faulkner et al. 2007, Janssen et al. 2005) which can vary significantly between different disciplines (Austin et al. 2015).

5 CONCLUSIONS

As models become more advanced, and complexity increases, the number of uncertainties present will also increase (Maslin 2013). For example, as highlighted by Klein (1998, p. 279):

- "Sometimes it is tempting to believe that we can use information technology to eliminate certain types of uncertainty. For example, an intelligent system could screen all messages to detect inconsistencies and weed these out. This dream is unrealistic. The next generation of computers will not eliminate uncertainty caused by inconsistencies."

There is thus a need to move towards approaches that do not just consider the suppression and reduction of uncertainty, but also acknowledge and incorporate uncertainty. This necessitates an increase in uncertainty tolerance (Han 2013) amongst both decision makers and advisers, and a move away from the 1949 deficit model of risk communication (see Daipha 2012, Markon and Lemyre 2013).

Doyle et al. (2014) highlights that contrary to the accepted anecdotal practice of not wanting to overwhelm decision makers with uncertainty information, on the assumption that the uncertainties will damage the trust and credibility of the decision maker, decision makers are often actually very comfortable with uncertainty (Doyle, McClure, Paton, et al. 2014, Johnson 2003, Johnson and Slovic 1995, 1998, Miles and Frewer 2003, Smithson 1999, Wiedemann et al. 2008). As stated by one emergency management participant in research by Hudson-Doyle et al. (2014) "uncertainty is endemic in crises, you just have to go with the best available information at the time". This relates to the Sword-Daniels (2018) concept of "embodied uncertainty", which considers uncertainty as both a conscious and subconscious lack of certainty. Such uncertainty is "differentially internalised, depending on past experiences, social identities, beliefs, values, institutional structures, resources available, and social norms" (p. 296). By broadening this concept of uncertainty, Sword-Daniels advocate for a shift in thinking towards "accepting (rather than reducing) uncertainty" (p. 296). As discussed by Klein (1998, p. 279), "skilled decision makers appear to know when to wait and when to act. Most important, they accept the need to act despite uncertainty."

Through this Insight paper, we have reviewed several factors and key issues relating to uncertainty and how that affects communication and data or information sharing throughout natural hazard events. We reviewed in section 1.1 the wide range of uncertainties that exist in a response, from uncertainty in actions through to the layers of uncertainties in data and models. We then outlined the literature on how people cope with uncertainty, and how their mental models of the data, their communication network with other individuals, and their needs and responsibilities, impact communications under uncertain situations (section 2) as well as how such mental models and epistemologies affect their interpretation of information and judgment of uncertainty in science advice (sections 2.1 and 4.1), and the role of trust in that process (section 4.2). We discussed the languages used and how typologies can be used to identify and categorise uncertainty in science and data, and how it can reduce the linguistic uncertainty (section 3). Finally, this was followed by a discussion of the importance of participatory approaches (section 4.3) to enhance effective communication of science advice by providing opportunities to identify decision-relevant information and uncertainty needs ahead of an event, such that in-event the data and information shared can be targeted to meet those needs. This also helps identify which of the many uncertainties in the data and models communicators should focus their communication efforts upon, which is of particular importance in high-pressure, time-limited, response environments.

We have highlighted the very multi-faceted nature of uncertainty, and propose uncertainty communication moves away from a one-way advisor led identification, analysis, and communication of uncertainties, towards these participatory type approaches that develop shared uncertainty management schemes. The currently accepted approach of a one-way 'science-push' communication of data, advice, and uncertainties, outlined by a number of organisational guidelines, may ensure advisers are honest, open and transparent. However, it may also result in the communication of information that is not useful, is unusable, and ultimately unused. It can result in decision makers needing to make time and resource intensive explicit requests for information in a crisis to address their decision needs (Kowalski-Trakofler et al. 2003, Lipshitz et al. 2001, Paton and Flin 1999), and can also result in information overload which can overwhelm the decision making process (Eppler and Mengis 2004, Omodei et al. 2005, Quarantelli 1997, Schraagen and van de Ven 2011).

Thus, as depicted in Figure 3, we propose that communicators, scientists, and advisers must develop coherent inter-agency/stakeholder relationships that include identifying the **decision-relevant uncertainties**, and related information and data ahead of a crisis event via participatory engagement with decision makers to ensure that communication efforts are focused upon the most relevant information required in the short time, high-pressure situations characteristic of natural hazards. In the absence of this activity, the scenario depicted in Figure (3a) will prevail. Requests for information will be ad hoc and based on agency/personnel reactions to events. Effective, functional inter-agency/stakeholder relationship development on the other hand, lends itself to the development of coherent shared models of relationships that have clarified respective information needs in ways that accommodate uncertainties. This affords opportunities to develop the kinds of relationships depicted in Figure 3(b) which creates ways to proactively respond to complex events. Through this, the implicit supply of information (and communication of only the decision makers' perceived relevant uncertainties) will enhance both the situation awareness and decision making of the response team. Pre-event two-way communication between decision-makers and advisers can help develop a mutual understanding as to the relevant uncertainties that need to be assessed and communicated for these decision needs (Blind and Refsgaard 2007). By communicating useful, useable, and used information (Aitsi-Selmi, Blanchard, et al. 2016, Rovins et al. 2014), we ensure that our advice abides by one of the core ethical principles of communication outlined by O'Neil (2002), that of "audience relevance" (see also Keohane et al. 2014). In addition, such an approach helps to ensure research is 'socially responsible' (Daedlow et al. 2016) in terms of societal goals and values, where the "transparent information and involvement of stakeholders during the research process can mitigate uncertainties and risks and is a morally responsible action" (p. 4). Such a partnership approach to identifying information needs also advocates for an approach that considers decision makers throughout the entire science generation process, right from the initial problem formulation, and not the traditional dissemination of science after results are identified. Thus, if during the reduction and readiness phases of emergency management, advisors adopt a participatory approach with decision-makers to identify, categorise and prioritise the uncertainties in their data, then their communication and data provision capabilities will be enhanced during the higher pressure response and recovery efforts.

Finally, we conclude this 'insight' review by highlighting that for all uncertainty communications used in any one-way or two-way process it is vital and imperative that they utilise communication tools, techniques, languages, and images that have been evaluated or empirically tested wherever possible (Bostrom et al. 2015, Briggs et al. 2012, Mastrandrea and Field 2010, Moss 2011). Unfortunately, as discussed by Doyle et al. (2018), this is not always the case (Benke et al. 2011, Bonneau et al. 2014, Bostrom et al. 2008, Boukhelifa and Duke 2009, Brus and Svobodova 2012, Deitrick and Wentz 2015, Hope and Hunter 2007, Tak et al. 2015), and to do otherwise may result in interpretations and actions that are significantly different to the intended and desired communication.

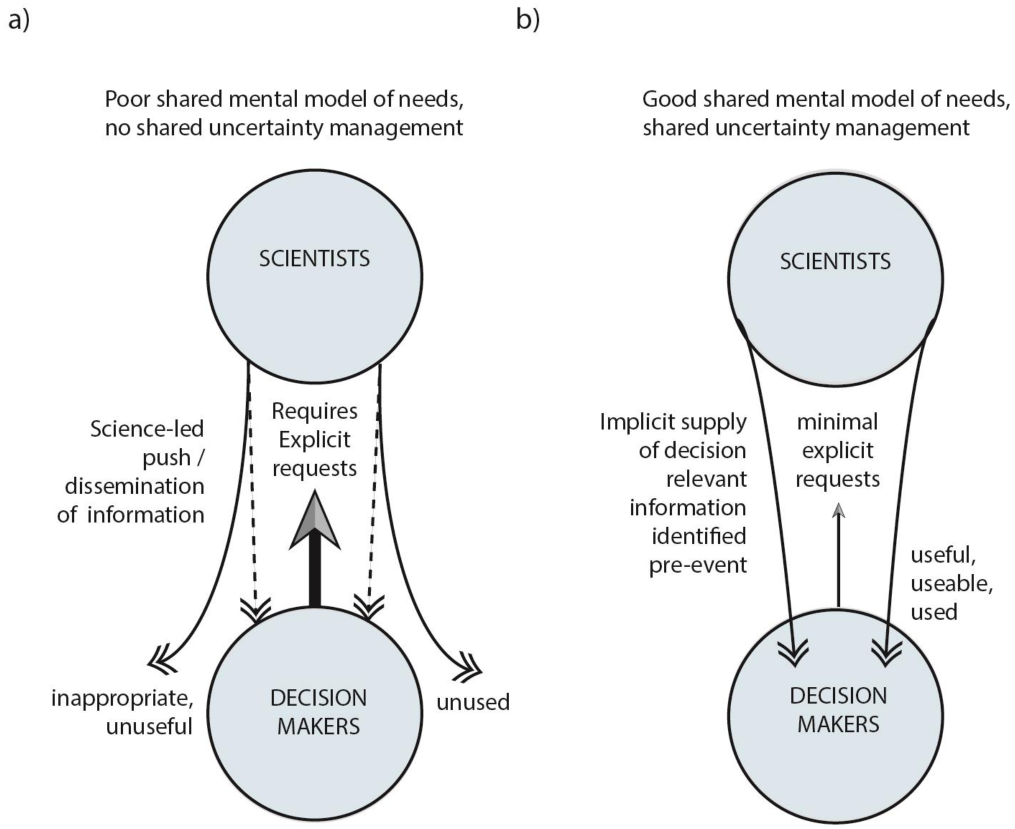

Figure 3: The importance of shared mental models and shared uncertainty management and communication schemes. a) When understanding of needs is weak, communication is dominated by disseminated information and requires time and resource intensive explicit requests from the decision makers for their needs to be met. b) When understanding of needs is good, and decision information needs are identified ahead of time, communication is dominated by implicit supply of tailored useful information and the decision makers only have to make minimal explicit requests.

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