1. Deliverable D5.1

Communicating seismic forecasts

Deliverable information	
Work package	WP5: Society: Data Gathering and Information Sharing with the Public and Policy-makers
Lead	University of Cambridge
Authors	Sarah Dryhurst, Giulia Luoni, Irina Dallo, Alexandra L.J. Freeman
Reviewers	Rémy Bossu, EMSC
Approval	Management Board
Status	Final
Dissemination level	Public
Will the data supporting this document be made open access? (Y/N)	N/A
If No Open Access, provide reasons	No original data is contained within this review
Delivery deadline	30.11.20
Submission date	30.11.20
Intranet path	DOCUMENTS/DELIVERABLES/Communicating seismic risk.pdf

27/11/2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821115

Table of Contents

"The right words at the right time can save lives"

(Sellnow, Iverson and Sellnow, 2017)

1. Summary

In the United Kingdom's House of Commons in 1854, a Member of Parliament stood up and made the suggestion that recent scientific advances might allow the weather in the city to be known 'twenty-four hours in advance'. The House broke into uproar and laughter - the idea was considered utterly preposterous. But with thousands of lives being lost in the country every year as a result of storms, by 1861 storm warnings were being wired to ports using the new telegraph system. As a by-product of this, the Meteorological Office charged with producing the warnings also sent a 'weather forecast' to the newspapers, saying "Prophecies and predictions they are not...the term forecast is strictly applicable to such an opinion as is the result of scientific combination and calculation." (*The Weather Book: A Manual of Practical Meteorology* (Fitzroy, 1863)).

Fitzroy, the father of the weather forecast, regularly replied to his critics in the media (who were usually complaining that bad weather had not been forecast) and had to deal with scepticism from scientific colleagues about his methods, funding problems from government, and complaints from those who lost business as a result of false alarms in the warnings. Tragically he killed himself as a result, only a few years after initiating the forecasting project, never seeing the weather forecast become a ubiquitous part of life worldwide.

Operational earthquake forecasting today finds itself in a rather similar position. We cannot tell whether, in 100 years' time, seismic forecasts will be as accurate and useful as forecasts of the weather became, but we can learn from the experience of fields such as meteorology and storm forecasting that have wrestled with many of the problems of communicating uncertain, dynamic, geographically variable, probabilistic information. In this report we aim to draw together the collective experience of multiple different fields, gathered through reviewing the academic literature and speaking to practitioners and researchers in a range of fields, whom we thank for their generous time and assistance.

Hopefully by learning from collective experience we can avoid repeating mistakes and develop inbuilt resilience to the pressures and criticisms that will inevitably fall on those who try to forecast.

THE WEATHER.

METEOROLOGICAL REPORTS.

Wednesday, July 31, 8 to 9 a.m.	B.	E.	M.	D.	F.	C.	I.	S.
Nairn..	29·54	57	56	W.S.W.	6	9	o.	3
Aberdeen	29·60	59	54	S.S.W.	5	1	b.	3
Leith	29·70	61	55	W.	3	5	c.	2
Berwick	29·69	59	55	W.S.W.	4	4	c.	2
Ardrossan . ..	29·73	57	55	W.	5	4	c.	5
Portrush	29·72	57	54	S.W.	2	2	b.	2
Shields	29·80	59	54	W.S.W.	4	5	o.	3
Galway	29·83	65	62	W.	5	4	c.	4
Scarborough ..	29·86	59	56	W.	3	6	c.	2
Liverpool.. ..	29·91	61	56	S.W.	2	8	c.	2
Valentia	29·87	62	60	S.W.	2	5	o.	3
Queenstown ..	29·88	61	59	W.	3	5	c.	2
Yarmouth.. ..	30·05	61	59	W.	5	2	c.	3
London	30·02	62	56	S.W.	3	2	b.	—
Dover..	30·04	70	64	S.W.	3	7	o.	2
Portsmouth ..	30·01	61	59	W.	3	6	o.	2
Portland	30·03	63	59	S.W.	3	2	c.	3
Plymouth.. ..	30·00	62	59	W.	5	1	b.	4
Penzance	30·04	61	60	S.W.	2	6	c.	3
Copenhagen ..	29·94	64	—	W.S.W.	2	6	c.	3
Helder	29·99	63	—	W.S.W.	6	5	c.	3
Brest	30·09	60	—	S.W.	2	6	c.	5
Bayonne	30·13	68	—	—	—	9	m.	5
Lisbon	30·18	70	—	N.N.W.	4	3	b.	2

General weather probable during next two days in the—
North—Moderate westerly wind ; fine.
West—Moderate south-westerly ; fine.
South—Fresh westerly ; fine.

Explanation.

B. Barometer, corrected and reduced to 32° at mean sea level ; each 10 feet of vertical rise causing about one-hundredth of an inch diminution, and each 10° above 32° causing nearly three-hundredths increase. E. Exposed thermometer in shade. M. Moistened bulb (for evaporation and dew-point). D. Direction of wind (true—two points *left* of magnetic). F. Force (1 to 12—estimated). C. Cloud (1 to 9). I. Initials :—b., blue sky ; c., clouds (detached) ; f., fog ; h., hail ; l., lightning ; m., misty (hazy) ; o., overcast (dull) ; r., rain ; s., snow ; t., thunder. S. Sea disturbance (1 to 9).

METOFFICE

An early weather forecast format from the UK's Meteorological Office.

2. What makes 'good risk communication' good?

What information do people want? What information do people need? And how can we best communicate that information?

These are the opening questions we all ask ourselves when starting to design communication material - but the problem with forecasts of potential disasters is that there is so much complexity: not just to the information, but to the uncertainty around them and to the psychological reactions of people receiving the information.

The field of 'risk communication' has been grappling with many of these aspects for some time. Risk communication can be defined as "any purposeful exchange of information about health or environmental risks between interested parties (Covello, von winterfeldt and Slovic, 1986). In this section we summarise some of the useful terminology, concepts and findings from the field of psychology and risk communication and how they relate to the specific problems of communicating earthquake forecasts.

2.1. Thinking about communication

There is a fairly simple model that dates right back to the 1940s and a researcher called Laswell (Lasswell, 1948), which is useful when studying communication:

WHO communicates WHAT, in WHAT FORM, TO WHOM, to WHAT EFFECT?

Of course, the real world of the media is far more complex, containing multiple intermediaries (Gladwin *et al.*, 2009), but breaking the elements of communication down in such a simple form like this allows us to be more specific about the variables involved and to clearly specify what combination we're actually studying.

The final part of this model – 'to what effect' – is the dependent variable, the thing that we are measuring, and defining what we measure and what we count as 'success' can be difficult to define.

For communicators who want to change people's behaviour – such as emergency messaging to evacuate – the desired effect is relatively clear and can be measured ('how many people would evacuate?' or, even better 'how many people DID evacuate?').

For communicators who purely want to inform their audience, to ensure that they understand the likelihood and potential impact of an event for which there is not an obvious, overwhelming 'right decision' (for example, informing policy-makers of long-term seismic hazard so that they can determine what sorts of planning policies are appropriate), measuring the desired outcome is more difficult. We can test whether they remember the numbers we have told them, but that tells us very little about their perception and understanding of what those numbers represent.

2.2. Risk and risk perception

"Risk does not exist independent of our minds and culture", (Slovic, 1992) *p690*

Imagine, for example, that someone had a 10% risk of dying from COVID-19 if they caught it. One in ten of people like them would die.

Imagine that risk applied to your child. That '1 in 10' figure would feel horrifying. One could imagine awful scenes at school with several children per class potentially dying.

Now imagine that that risk applied to your 95 year old, very ill mother (a much more realistic scenario, incidentally, as a 10% risk is high). '1 in 10' people like her dying of COVID if they catch it would be very sad, of course, but not a shocking surprise. That 10% feels somehow different.

Thus there is an important distinction to be made between a risk and the perception of it. Whilst you can use objective calculations and expert assessment to calculate hazard and exposure, risk perception itself is a mental construct that combines this objective "real risk" with its subjective, perceptual evaluation (Sjöberg, 2000; Rosa, 2003). As such, perceived risk may differ substantially from expert assessments of "real risk" ((Starr, 1969; Slovic, Fischhoff and Lichtenstein, 1982)), and this perceived risk is not 'wrong' if it varies from the numerical, calculated absolute risk as long as it is not based on a misunderstanding of that absolute risk.

This was a classic mistake made early in research into risk communication: judgements of risk were assumed to be made in line with 'expected utility' (i.e. people should 'do the maths' and that would give 'the right decision to make' in order to maximise or minimise a particular outcome) ((von Neumann and Morgenstern, 1944; Edwards, 1954; Jeffrey, 1983)). Where judgements were irrational, it was assumed that this was due to lack of knowledge about the situation or subject; a framework known as the 'knowledge deficit model'. It meant that people concentrated mainly on 'reducing the knowledge deficit' - trying to 'educate' people with more and better information about the risk under consideration (Millet *et al.*, 2020).

Instead, it's more useful to think about risk as having different components. When talking about natural hazards it is sometimes formally conceptualised as:

Risk = hazard x exposure x vulnerability

Here, the *hazard* is a manmade or natural event that has the potential to cause harm, and encompasses both how big the event is (*severity*), and how often it occurs (*likelihood*). *Exposure* relates to what elements are at risk from the hazard in question, and their density (for example is it people, agriculture, buildings etc). Finally, *vulnerability* relates to the characteristics of the exposed elements that makes them susceptible to damage by the hazard in question (Doyle and Potter, 2015).

Vulnerability may be physical (the potential for physical impact on the built environment or the population), social (the response of individuals or groups to the hazard), economic (direct or indirect economic costs) or systemic (the disruption to delivery of services such as telecommunication or power) and is defined differently by researchers in different fields (Geoscience Australia, 2020).

The magnitude of these three components of risk can vary depending on the space and time over which each is considered - and that, of course, depends on who the audience is. For example, a national policy maker might be interested in time frames similar to the term of their office, and over a nationally representative area; a local government official might be interested in a smaller geographical region only; a building manager might only be interested in the risk as it applies to their specific building, but might be interested in a much longer time frame if the lifecycle of the building is, say 50 years.

The vulnerability component is the one that is perhaps the most subjective and difficult to quantify. Whilst it is easy to start trying to think of risks simply as numbers, it is clear when you consider how you might define the vulnerability of a person or a society that risks are not an objective, numerical concept.

The effect of human psychology and sociology on people's individual concepts and perceptions of a risk therefore have multiple components – and it is important to have an overview of these when considering how best to communicate risk and hazard information.

2.2.1. How we understand factual information

We are limited in how much information we can process. Research suggests we are capable of storing just 3-4 "chunks" of information at any one time (e.g. (Shiffrin and Nosofsky, 1994; Doumont, 2002; Kane and Engle, 2003). Whilst quality of decisions increases with information available initially, after a certain point adding more information reduces performance (Chewning and Harrell, 1990). Thus simply providing more information does not always lead to better comprehension or higher quality decision making, especially in people who are less numerate (Peters, 2008)

Cognitive psychologists got excited about researching how we decide what information to pay attention to and base our ideas on.

We all use 'cognitive heuristics', shortcuts that focus on key pieces of information and ignore others (Tversky and Kahneman, 1974b). These generally help us make quick decisions, and can sometimes lead to more 'rational' judgements than a more deliberative process might (Gigerenzer and Brighton, 2009). However, heuristic thinking can be subject to predictable biases and result in 'irrational' judgements and decisions, including misperceptions of risk or failing to prepare or react in the way most likely to protect ourselves from harm e.g. (Van Vugt, Griskevicius and Schultz, 2014; van der Linden, 2017).

A few relevant biases include:

- 'Availability bias': things that are 'near the front of your mind' seem more likely. For example, people often take out insurance against an event after it has happened (Tversky and Kahneman, 1973).

- ‘Normalisation bias’: related to the availability bias, what we have experienced in the past seems the most likely outcome in the future, making us less responsive to varying levels of risk (Mileti and O’Brien, 1992).
- ‘Anchoring bias’: the first piece of information we hear about a topic tends to have more weight than subsequent information, which is interpreted in the light of what we’d previously heard (Tversky and Kahneman, 1974a).
- ‘Confirmation bias’ and ‘motivated reasoning’: we tend to look for and better remember information that confirms what we always thought, and not like information that challenges our prior beliefs; and we interpret evidence to suit the decisions we already want to make (Kunda, 1990).
- ‘Optimism bias’: we tend to think bad things are unlikely to happen to us (Sharot, 2011).

The more cognition is “overloaded” by the provision of too much information, the more likely we are to rely on these cognitive heuristics, and potentially fall foul of their biases when processing information and making decisions. Since stress uses up cognitive resources (Qin *et al.*, 2009) we may be even more challenged in our information processing capabilities during the crisis phase of disasters, and more susceptible to these biases in judgement and decision making.

Rather like visual illusions, it’s popular to show examples of where people have reacted to hazards in irrational ways, for example discounting certain risks such as not preparing for hurricanes despite living in high risk areas e.g., (Baker *et al.*, 2012; Ricchetti-Masterson and Horney, 2013).

Psychologists like to separate the mental short-cuts of ‘heuristics’ from more in-depth ‘sitting down and thinking about it’ and call this ‘dual-process’ thinking (Evans, 2003, 2008, 2011; Evans and Stanovich, 2013), commonly known through the book ‘Thinking Fast and Slow’ (Kahneman, 2011). They call the fast, heuristics “Type I” processing and the slower, more reflective thinking “Type II”. Communications might be designed either to minimise biases whilst accepting that people are going to be using ‘Type I’ everyday thinking (e.g. the design of a weather app for people to glance at), or they might try to encourage ‘Type II’ thinking (e.g. the design of a report for policy-makers who have the time to make a considered decision). Of course, decisions and conclusions from either kind of thinking are not necessarily ‘better’ than each other. Type II thinking is capacity-limited (Baddeley, 1992), but it might also encourage us to try to exclude some of our natural emotions and experience, which can be important when making decisions and taking action (Peters and Slovic, 2000).

2.2.2. The effect of feelings and experiences

As research has progressed over the last 50 years, it has become clear how important a role our emotions (what psychologists call “affect”) and experience have to play in our perception of and response to a risk.

One aspect of this is the feelings that are evoked by the idea of the risk itself. Evidence suggests that we are influenced by two key psychological dimensions: “dread” risk, which describes hazards that are characterised by lack of control, feelings of dread and perceived catastrophic potential, and “unknown” risk, which describes hazards that are unobservable, unknown, new or delayed in consequence (Fischhoff *et al.*, 1978; Slovic, Fischhoff and Lichtenstein, 1981; Peters and Slovic, 1996).

Our feelings about a risk play a vital role in our in information-seeking and processing. Our experience and associated emotions interact with and moderate more deliberative, cognitive assessments of risk (Loewenstein *et al.*, 2001; Slovic *et al.*, 2004). This idea of “risk as feelings” is perhaps best described by what is called the “affect heuristic”, whereby people judge the riskiness of hazards based on a pool of positive or negative emotions they associate with that hazard (Finucane *et al.*, 2000; Slovic *et al.*, 2007). Under the affect heuristic, judgements of risk may be expected to be influenced by whether or not an individual has had experience with that hazard, and in turn what the emotional nature of that experience was; the more experience one has had, the more positive or negative “tags” that particular hazard has and the greater the influence of that experience on risk perception (Damasio, 1994). The more negative tags associated with a risk, the more risky that thing is perceived to be (Damasio, 1994).

There have been many studies examining the effect of experience on perceptions of and behaviours regarding hazards in a practical sense. For example, several studies have shown that those who have a higher perception of the risk, and have directly experienced hazards, tend to seek out mediated information (such as news broadcasts) and are more likely to take precautionary measures than people who have never experienced them before (Dash and Gladwin, 2007; Armstrong, Cain and Hou, 2020). Furthermore, there is evidence that those who have had even indirect hazard experience tend to have an emergency plan (Maduz *et al.*, 2019). However it is also possible that those who have experienced a mild form of a hazard event may be more likely to underestimate the potential danger of such a hazard. This could be because of “normalization bias”, (Mileti and O’Brien, 1992) when people interpret the impact of the event they have experienced as the norm and do not appreciate how much worse, (or better!), such an event can be (e.g. having experienced a mild earthquake, not realising what a really intense one could be like or vice versa).

Over time, people begin to forget about their experience (what’s been called “half-time of oblivion” (Wagner, 2004)). When the salience of a hazard lessens, there is a concern that people can become less information-seeking (Hagemeier-Klose and Wagner, 2009). This might be particularly problematic for the communication of high impact low probability events such as earthquakes, where even though the impact of the event can potentially be catastrophic, the frequency of the event is low and thus easy to forget with the passing of time.

On top of all that, in some circumstances we seem to behave as though we have limited emotional resources (Linville and Fischer, 1991). This idea was been expanded into a ‘finite pool of worry’ theory – that there’s only so much that we can worry about at any one time (Hansen, Marx and Weber, 2004), although the COVID-19 pandemic provides evidence that worry about COVID-19 did not decrease worry about other hazards (A. L. J. Freeman, Schneider, *et al.*, 2020; Sisco *et al.*, 2020), only distract attention. We shouldn’t, though, try to ‘make people worry’ about things that it is unreasonable to expect them to worry about given their other concerns, and higher levels of risk perception do not necessarily translate into protective action – there are so many other factors that again continue to act.

2.2.3. The role of trust and authorities

When we hear messages, our level of trust in the institutions communicating to us has an influence on our response to the messages (Slovic, 1993). People tend to place trust in those they believe to be knowledgeable about a particular risk and who are willing to share accurate information about it (Earle and Cvetkovich, 1995; Slovic, 1999, 2000; Siegrist and Cvetkovich, 2000; Lang and Hallman, 2005; Coles and Hirschboeck, 2020). Indeed trust in both information and its source have been shown to be important influences on the adoption of preventative behaviours for a hazard event (Paton, 2007; Morss *et al.*, 2016).

Naturally, people are more likely to act on information from trusted authorities (Siegrist and Zingg, 2014). Those who do not have personal knowledge about the issue at hand tend to rely on trust in authorities more (Siegrist and Cvetkovich, 2000). Not surprisingly, information coming from a responsible authority (Bean *et al.*, 2015) or even better a central federal agency is more likely to be an object of trust with a large proportion of the population (Maduz *et al.*, 2019). Trust in a particular institution may be lost if it is perceived to be removed from extreme events and regular, daily situations (Parker and Handmer, 1998; Savadori *et al.*, 2004), potentially leading to people seeking information from alternative sources in which they place higher trust (Mileti, 1995; Parker and Handmer, 1998; Coles and Hirschboeck, 2020). (The definition of, and components of, trust is another large area of study, but it broadly encompasses judgements on expertise and motivation & integrity).

Research suggests that users' trust in disaster warning apps can be influenced by perceived quality (Karl, Rother and Nestler, 2015), reliability (Kaufhold *et al.*, 2018) and privacy and security (Fischer, Putzke-Hattori and Fischbach, 2019), whilst user perceptions and uptake of hazard technologies, and the extent to which they follow behavioural advice provided in warnings by them, is influenced by how trustworthy they perceive the app to be (Siegrist and Cvetkovich, 2000; Kotthaus, Ludwig and Pipek, 2016; Appleby-Arnold *et al.*, 2019).

However, there are additional barriers to action on a message – one of which appears to be that some people expect the authorities to protect them and do not perceive disaster preparation to be their own responsibility (making sure to have their own preparations in case an event occurs)(Scolobig, De Marchi and Borga, 2012). Trust, then, can be a negative as well as a positive in terms of encouraging preparedness.

2.2.4. The influence of the media, society and culture

We do not receive and react to information in a vacuum. Humans are essentially social animals, and a lot of our behaviour is affected by our social values and the perceptions of others.

The 'Social Amplification of Risk Framework' (Renn *et al.*, 1992; Pidgeon, Kasperson and Slovic, 2003; Kasperson *et al.*, 2016) is a theoretical approach that highlights the roles of social norms, interpersonal interactions and the mass media in how perceptions of risk are formed (van der Linden, 2017). Despite qualitative evidence of the social amplification of risks (e.g.(Barnett and Breakwell, 2003; Renn, 2011; Smith and Joffe, 2013) it's very difficult to quantify the causal effects of social influences on risk perception (Renn, 2011) although there has been some work in this area (e.g. (Jones *et al.*, 2013; van der Linden, 2015; Dryhurst, Schneider, *et al.*, 2020)

Several frameworks have also been developed that attempt to integrate a psychological approach with the influence of values, worldviews and the broader structure and functioning of society. An early approach was the "Cultural Theory of Risk" (Douglas, 1970; Douglas & Wildavsky, 1982; Dake, 1992) which divides people into four broad cultural worldviews that define the relationship an individual has to society and how this affects their risk perceptions. These groups include hierarchism (communitarian individuals who favour hierarchical, regulatory societal structures), fatalism (individualists who favour hierarchical, regulatory societal structures), egalitarianism (communitarian individuals who do not favour such structures) and individualism (individualists who do not favour such structures).

More recently the "cultural cognition thesis" (Kahan, 2012) divides people more simply on two dimensions; hierarchy-egalitarianism and individualism-communitarianism, and suggests that people are motivated to accept and integrate information about a risk that is consistent with their existing worldviews ("identity protective cognition") and thus again suggests that individuals vary in their risk perception depending on where they lie on these dimensions.

Research suggests that worldviews can have small but significant effects on risk perception, for example, individualists tend to have lower risk perception of a variety of hazards, including climate change (Leiserowitz, 2006; Kahan *et al.*, 2012; Smith and Leiserowitz, 2012; Xue *et al.*, 2014) and infectious diseases (Dryhurst, Schneider, *et al.*, 2020). Individuals and cultures also differ in their degree of fatalism towards natural disasters, although a meta-analysis by Xue *et al.* (2014) of 67 effect sizes from a pooled sample of 15,660 people showed no significant relationship between fatalism and environmental risk perceptions. Some may blame the occurrence of catastrophic events or natural calamities on 'transgressive behaviours' in order to try to discourage behaviours they consider unacceptable (Douglas, 1992), and others on supernatural powers (Paton *et al.*, 2010; Richard Eiser *et al.*, 2012). For example, many religious leaders consistently associate earthquakes with homosexual behaviour (The Atlantic, 2010; The Guardian, 2015; BBC News, 2016; The Independent, 2016).

2.3. 'To what effect'?

How, then, can we measure 'risk perception'? A good set of criteria were laid out by Weinstein and Sandman (Weinstein and Sandman, 1993):

1) Comprehension (Does the audience objectively understand the content of the communication?), which can be measured through simple knowledge-based questions.
2) Agreement (Does the audience agree with any interpretation or recommendation included in the message?), which may only be relevant in messages that contain advice.

3) Dose-response consistency (Do people facing a higher impact or dose perceive the risk as greater or show a greater readiness to take action than those facing a lower impact or dose?)
4) Hazard-response consistency (Do people facing a higher likelihood of an outcome perceive the risk as greater or show a greater readiness to take action than those facing a lower likelihood?)
5) Uniformity (Do audience members shown the same level of risk in a communication tend to have similar responses to it?)
6) Audience evaluation (Does the audience subjectively find the message helpful, clear, accurate etc?)
7) Failure-type (What types of failure of the communication are possible and if they occurred would they be acceptable?)

Not all of these will be relevant to every communication, but they do provide a useful framework when designing evaluation studies.

2.4. The gap between feelings, perceptions, knowledge, and behaviour

Awareness and risk perception are important, but not sufficient for people to take protective action. If the goal of your communication is behaviour change, then there are a few more potential barriers. Protection-motivation theory (Rogers, 1975) proposes that there are four factors involved in people's decision to take action: the perceived likelihood, severity and vulnerability that makes up the risk perception but also another factor: the feeling that there are actions that will make a significant difference (response efficacy) and that they themselves can do them effectively (self efficacy). The protective action decision model (Lindell and Perry, 2012) adds in social norms.

2.5. Risk communication - summary

'Each of us has to decide what the right balance is between being effective and being honest. I hope that means being both' (Schneider, 2002)

Good risk communication depends on an understanding of how the various audiences perceive the risk being communicated (Spiegelhalter, 2017). This perception of a risk that people hold in their minds, however, is rarely a direct replication of the actual quantified risk. Risk and the perception of risk, then, are two distinct concepts. The way that a risk is perceived is not based purely on rational weighting of likelihood and impact, but is in fact a combination of information and our psychological reaction to that information. Thus simply providing one's audience with more information (i.e. increasing their knowledge) about a particular risk might not be the most effective communication strategy, at least not in isolation. Instead, consideration of an individual's personal experience and situation, psychology and the culture and society within which they are embedded is essential in understanding how they might perceive a risk you are trying to communicate, and thus in designing that communication (Renn, 2008). This may be particularly important where the risk is low in probability but high in impact, ‘dread’ or ‘uncertain’; some or all of which may apply to the communication of earthquake risk.

Careful consideration of the aims of the communication, and how success might be measured in an evaluation, is also vital. Do people understand the communication in a deeper sense than simply remembering the numbers? And are they in a position to, and mindset to, act on it? A key part of theoretical evaluation could be to measure hazard and/or dose response consistency: whether higher risk numbers (in terms of likelihood or impact) result in a correspondingly higher response from the audience in terms of salience of that information in their decision-making. The only real evaluation, though, is one done in the real world, when an event happens.

3. Why is it hard to communicate an earthquake forecast?

The precise timing and location of an earthquake event cannot be predicted accurately (Geller *et al.*, 1997). What is available however, are time-dependent and location specific probabilistic forecasts of earthquake occurrences, from models that combine localised time-dependent earthquake clustering models and time-independent models based on historical earthquakes and fault data (Gerstenberger *et al.*, 2005). As such, these "Operational Earthquake Forecasts" provide spatially and temporally dynamic information on the changes in likelihood of an earthquake event in real time (e.g. (Jordan *et al.*, 2011, 2014; Gerstenberger *et al.*, 2014; Field *et al.*, 2016; Marzocchi, Taroni and Falcone, 2017)).

The aim of Operational Earthquake Forecasting (OEF) is to disseminate authoritative information about time-dependent probabilities of future earthquake hazard and risk, to help communities prepare for potentially destructive earthquakes (Jordan *et al.*, 2014; Becker *et al.*, 2020). OEFs are now produced by several countries worldwide, including the US, New Zealand, Italy and Japan.

Some researchers have criticised the usefulness of OEF in an operational sense (e.g. (Peresan, Kossobokov and Panza, 2012; Wang and Rogers, 2014). These have been discussed and rebutted at length by (Jordan *et al.*, 2014), however one of the most common criticisms bears mentioning here: that effective building evacuations are the most impactful emergency management decisions that can be taken prior to an earthquake event, and that such evacuation decisions cannot be made on the low probability gain information that OEF typically provides (Wang and Rogers, 2014). While it may be true that no risk manager would decide to perform a full scale evacuation on a change in probability from 0.001% to 5%, evacuations can be made lower cost by targeting those building that are weakest and on the poorest soil, making it a more feasible option (van Stiphout, Wiemer and Marzocchi, 2010). Additionally, during aftershock sequences, probability gains may be much larger providing stronger grounds for higher cost action. In turn whilst earthquake events are typically treated as acute, with short periods of impact, the response to which transforms quickly into a phase of recovery, the occurrence and impacts of prolonged aftershock sequences such as the Canterbury Earthquake Sequence (New Zealand) or Ridgecrest (California) highlights a need for communication of this continuous and dynamically changing background risk to inform decision makers undertaking risk management (Becker et al. 2019). This is something that OEF can provide, and during the Canterbury and Cook-Strait earthquake sequences in New Zealand, was shown not only to be useful to emergency managers, but also to encourage personal actions by members of the public, including self-evacuations (Gerstenberger *et al.*, 2014).

There are also several low-cost uses to which OEF can be put in an operational context, such as rehearsing disaster response scenarios in drills, reissuing preparedness advice and increasing the readiness of emergency response (Jordan *et al.*, 2014; Woo and Marzocchi, 2014). Indeed, in the US, OEFs are used by emergency managers to advocate for both organisational and household preparedness (e.g. (Goltz, 2015; McBride *et al.*, 2019)), whilst in New Zealand aftershock forecasts have been put to a variety of purposes, informing decisions about things like safe access into buildings, demolition and timing of repair, rebuilding operations and public communication (Julia Becker *et al.*, 2015; Becker *et al.*, 2019, 2020). Although stakeholders were uncertain about how to apply these aftershock forecasts to decision making during response and recovery processes, Becker et al. (2020) go on to suggest that scientists should work with communities in the development of aftershock forecasts such that they can be tailored to the specific needs of each individual audience. In turn it is recommended that such communications should include recommendations for specific actions that can be taken in response to the forecast to reduce risk.

The public too can put the low probability gains that OEF provides to use in low cost actions such as checking emergency supply kits are complete and that mounted items are securely fixed to the walls of their homes. Becker et al., 2020 showed that, in the aftermath of the 2016 Kaikoura earthquake, the public did use aftershock forecasts to inform their decision making regarding, for example, securing furniture to walls or securing the foundations of their houses.

Beyond operational value, OEF can also have psychological value (Jordan *et al.*, 2014). For example (Wein and Becker, 2013) demonstrated that the public of Christchurch greatly valued OEF information during the Canterbury Earthquake Sequence, particularly the simple knowing that earthquake aftershocks were behaving in the manner expected by experts. There is also an ethical element: should a relative risk increase of several orders of magnitude be left unreported to those whose lives may be in danger in the event of seismic activity, or policy-makers and managers of significant infrastructure (such as power stations, bridges or tunnels)?

Clearly then, although not a forecasting panacea, OEF has value to a variety of audiences both prior to and during earthquake events and sequences (see (Becker *et al.*, 2020) for a thorough analysis and review). To maximise its value however, it must be communicated in a clear, comprehensible, trustworthy and actionable way. This raises at least four significant issues.

3.1. The challenge of rare events

Earthquakes happen all the time. But damaging earthquakes are rare - and in any particular geographic location, very rare indeed.

This presents us with several problems. One is that people struggle to understand small probabilities (Camerer and Kunreuther, 1989; Halpern, Blackman and Salzman, 1989; Lipkus, 2007).

We don't really understand how people process small probabilities in their minds (Lipkus, 2007). According to prospect theory, people are expected to underweight small probabilities (Kahneman and Tversky, 1979), and there is evidence in the literature for this effect (e.g. (Hertwig *et al.*, 2004)). There is also evidence that people sometimes dismiss small probabilities entirely (e.g. (Stone, Yates and Parker, 1994)). However other studies have shown that people sometimes overestimate probabilities where outcomes are affect-laden (emotionally charged)(Rottenstreich and Hsee, 2001), whilst others still have shown explicit bimodalities in response within the same study, with some people overestimating and others underestimating (e.g.,(McClelland, Schulze and Hurd, 1990; McClelland, Schulze and Coursey, 1993)).

Adding to this, comparing between different small probability events is difficult – people appear to struggle to distinguish between small numbers, although there is not a huge amount of empirical evidence (Kaplan, Hammel and Schimmel, 1985; Cohen, Ferrell and Johnson, 2002). For example, say we forecast that there is a 0.0001% chance of a magnitude M7 earthquake occurring at a particular location, but the next day we forecast a 0.001% chance – the two numbers are likely to be difficult to perceive as an order of magnitude different. If people struggle to perceive a difference between these two small numbers, then they miss the vital information that the risk, whilst still low, has increased 10 fold.

The rarity of events also makes it difficult for forecasters to assess the confidence in their forecasts, as there is not a lot of data to check against. Nor is there a good track record of forecasts for the public to learn from: unlike everyday weather forecasts, no one is being able to constantly check the accuracy of forecasts over a period of time.

All of these factors make the communication of these high impact but low probability events difficult. But earthquake forecasters are not alone: several fields suffer from the problem of having to communicate small probabilities or numbers, and throughout the review we have looked for empirical work of relevance from any domain.

3.2. The challenge of dynamically varying risks

Seismic activity is, of course, constantly changing. During active phases, there might be changes in a particular geographical region hour-by-hour which need to be communicated. During quiescent phases there may be no change in risk for years at a time. This huge range of variability over time, added to the spatial nature of the risk, makes it particularly difficult to communicate as audiences in most regions will not experience heightened risks very often.

Several fields (e.g. storm forecasting) face similar challenges, and so in this review we again attempt to pull together best practice and empirical work from such domains.

3.3. The challenge of high uncertainty

Everyone understands that it is not possible to predict the future. The word ‘forecast’ was used by Fitzroy when describing his weather forecasts in order to avoid the trap of ‘prediction’. This is down to a kind of uncertainty known as ‘aleatoric’ (from the Latin for throwing dice): it is inevitable and due to the random factors of the universe. It means that everything we communicate about the future will inevitably be a likelihood or probability: the chances of something happening.

But unfortunately that’s not the only kind of uncertainty. Just to get some more terminology out of the way:

'Epistemic' uncertainty is the term used for uncertainty from a lack of knowledge about things that could theoretically be established. Epistemic uncertainty often applies to past and present events although it can also apply to future projections. For example, predictions about what sort of damage a building might sustain during an earthquake of a given intensity will contain epistemic uncertainty - uncertainty caused by parameters in the model that could in theory be known, not being known (e.g. the current state of the building's internal structures).

'Ontological' uncertainty describes uncertainty about whether one understands reality sufficiently such that one's modelling process is a true reflection of it (Spiegelhalter, 2017; van der Bles *et al.*, 2019) Whilst aleatory and epistemic uncertainty may be classed as "known unknowns" (to use the terms of the infamous Donald Rumsfeld quote) and can to some extent be modelled or quantified, ontological uncertainty reflects "unknown unknowns" expressed as a qualitative, subjective assessment of the representativeness of the model (Spiegelhalter, 2017). And with earthquake forecasts, there are plenty of ontological uncertainties.

Each of these different types of uncertainty can have different effects on the audience. For example, communicating the epistemic uncertainty as a numerical range (such as a confidence interval) does not appear to undermine trust (van der Bles *et al.*, 2020), whilst communicating a lower quality of evidence behind an estimate can (Schneider *et al.,* in prep).

Although the public appears to have a natural sense of understanding about aleatoric uncertainty, and hence infer uncertainty from even deterministic weather forecasts – hence explaining their willingness to accept probabilistic forecasts (Morss *et al.*, 2008; Joslyn and Savelli, 2010) – the much higher degree of uncertainty around seismic forecasts, and the lack of familiarity that the public have with it, make it a particularly daunting challenge.

3.4. The challenge of misinformation

In February 2009 a local man working as a technician at the Gran Sasso National Physics Laboratory near L'Aquila in Italy made a series of amateur earthquake predictions based on radon gas concentrations. Widely reported, and with one of them being followed by a shock shortly after he made a public warning, these caused many citizens to evacuate their towns. The rising public concern, fanned by this misinformation, forced government geoscientists to make public statements about the absolute probability of a large earthquake remaining very small, and culminated in the infamous meeting and press conference on 31st March that year, designed to reassure the public, and which resulted in the legal trial after the tragic earthquake that occurred only days later (Alexander, 2010; Jordan, 2013a).

Misinformation, then, is of deep concern to seismic forecasters.

Misinformation is information that is initially presented as true but subsequently found to be false (Lewandowsky, Ullrich K.H. Ecker, *et al.*, 2012). Misinformation can be disseminated actively with the intent to deceive (in such instances it is sometimes referred to as disinformation), however this is not always the case. An unfolding event such as a natural disaster may see initial reported damage or death tolls updated at a later date once more information is received (Cook, Ecker and Lewandowsky, 2015). Either way, misinformation is a global problem affecting many diverse topics including climate change (Oreskes and Conway, 2010; van der Linden *et al.*, 2017a; Farrell, McConnell and Brulle, 2019; Maertens, Anseel and van der Linden, 2020), COVID-19 (BBC News, 2020; D. Freeman *et al.*, 2020; Jolley and Paterson, 2020; Roozenbeek *et al.*, 2020), politics (Allcott and Gentzkow, 2017; Lee, 2019), vaccinations (Gangarosa *et al.*, 1998; Poland and Spier, 2010; Lewandowsky, Ullrich K. H. Ecker, *et al.*, 2012), and natural disasters (Whitney, Lindell and Nguyen, 2004; Alexander, 2010; Takayasu *et al.*, 2015; Fallou *et al.*, 2020; Hunt, Wang and Zhuang, 2020) The spread of misinformation can potentially undermine both science and society (Lewandowsky, Ecker and Cook, 2017; Linden *et al.*, 2017; Roozenbeek and van der Linden, 2019b). Indeed, a study of the US public by (Barthel, Mitchell and Holcomb, 2018) showed that many Americans said that fake news left them confused about even basic facts, and misinformation has been ranked by the World Economic Forum (World Economic Forum, 2014) as one of the major risks threating countries across the globe.

Misinformation can emerge from a variety of sources, both traditional media and online (Cook, Ecker and Lewandowsky, 2015; Painter and Gavin, 2016), and has been shown to have considerable influence on beliefs and behaviour in many areas. Several studies have shown that misinformation about climate change undermine beliefs in climate change being anthropogenically caused (Cook, Lewandowsky and Ecker, 2017a; van der Linden *et al.*, 2017a), whilst misinformation about the measles-mumps-rubella (MMR) vaccination that erroneously suggest it is linked to autism have had a significant negative effect on vaccine uptake in many countries (Gangarosa *et al.*, 1998; Poland and Spier, 2010).

In a foundational study by (Turner, Nigg and Paz, 1986) in which they surveyed a representative sample of 1450 Southern Californian residents, it was discovered that 43.5% of participants believed that unusual weather might be a predictor of earthquakes, while 67.5% thought that unusual animal behaviour was a predictor. (Whitney, Lindell and Nguyen, 2004) investigated belief in a variety of earthquake myths and facts in a sample of Southern Californian college students, and how this influenced their levels of seismic hazard adjustment. Whilst certain beliefs (erroneous or factual) might be expected to increase seismic hazard adjustment, others such as the belief that earthquakes are predictable might reduce the motivation to prepare, especially where people are waiting for a warning of such a predicted earthquake. (Whitney, Lindell and Nguyen, 2004) demonstrated that although a substantial minority of participants agreed with both the assertion that earthquakes could be predicted and that they would receive a warning telling them of an impending earthquake, when they examined the relationship between beliefs in the myths and seismic hazard adjustment, the results were mixed. In one of their subsamples of participants they found a weak, negative correlation between belief in the predictability of earthquakes and seismic hazard adjustment (people who endorse this belief more were less likely to prepare), however this relationship was not significant in the full sample. Contrary to their expectations, they found a significant positive correlation between the belief that participants would receive a warning and levels of seismic hazard adjustment in their full sample, but this relationship was not significant in the subsample.

A later study by (Becker *et al.*, 2013), conducted 48 qualitative interviews with residents of locations in New Zealand subject to seismic risk, and found that belief in the idea that people would receive a warning about various natural hazards did in fact reduce preparedness in several of their participants, although they noted that this did not apply so much in the context of earthquakes. Further research, however, is required to confirm the impacts of false beliefs on seismic hazard adjustment.

In a detailed case study of citizen seismology and misinformation in the French island of Mayotte, (Fallou *et al.*, 2020) found that, in the wake of the 2018 earthquake swarm experienced by the island, 10,000 people in the local community formed an online citizen seismology group. They went on to show that, although certain members of this group did share legitimate seismological information, misinformation and conspiracy theories also emerged. (Fallou *et al.*, 2020) assert that the lack of seismic data, scientific information and communication from authorities during the earthquake swarm opened up an information void that misinformation could fill. They also showed that this resulted in mistrust of a variety of seismological organisations.

4. What research can tell us about overcoming these challenges

Many of the challenges outlined in the previous section are faced by fields other than seismology, or even other natural hazards. Although in this review we dedicate individual chapters to particularly similar fields and review the literature pertaining to each individually, here we give an overview of what academic research in general has been done on each topic.

4.1. The challenge of rare events

As discussed earlier people struggle to understand small probabilities (Camerer and Kunreuther, 1989; Halpern, Blackman and Salzman, 1989; Lipkus, 2007), sometimes under-weighting them and sometimes over-weighting them. In turn, people find it difficult to compare between small numbers and thus between different, low probability events.

4.1.1. Choosing what numbers to display

There are several ways of presenting numbers that can affect people's interpretations of the small probabilities that are associated with rare events.

One example is by changing the time frame over which they are presented (for example estimating one's risk of death from a car crash within a day versus within ten years); people tend to perceive more danger when risks are communicated over a longer time frame than a shorter one (e.g. (Slovic, Fischhoff and Lichtenstein, 1978; Keller, Siegrist and Gutscher, 2006; Bonner and Newell, 2008)). If time frames are too long, though, it's possible that people may begin to discount the risk, feeling like it is not relevant to them in their lifetime. Indeed people have different preferences for different time frames, tending to choose one that is relevant to them (Schapira, Nattinger and McHorney, 2015).

Another example is that presenting numbers in frequency (x times out of 100) rather than percentage format increases the perception of the risk of an event (e.g. (Siegrist, 1997; Slovic, Monahan and MacGregor, 2000; Keller, Siegrist and Gutscher, 2006; A. L. J. Freeman, Kerr, *et al.*, 2020)), perhaps because it makes it easier to imagine the event in question and thus attach emotion to it, or perhaps because this fits better with our evolved techniques of acquiring information in the natural world (Gigerenzer and Hoffrage, 1995; Cosmides and Tooby, 1996), whereas a percentage gives a less tangible sense of a real event (Slovic, Monahan and MacGregor, 2000; Keller, Siegrist and Gutscher, 2006). When using a frequency format, though, if the audience is being asked to compare risks, it is important to keep the denominator the same (i.e. avoiding '1 in x' where x is variable). Otherwise there is a tendency for people to be misled by the size of the numerators whilst neglecting the changing denominators (Yamagishi, 1997). Larger denominators – such as 'out of 1000' make the risks seem bigger than the same frequency expressed as 'out of 100', possibly because the numerators are generally larger (A. L. J. Freeman, Kerr, *et al.*, 2020). This finding translates to time periods; (Bonner and Newell, 2008) found that '2900 people die per year' was rated riskier than '8 people die per day'.

Whilst the absolute risks of an event happening may be small, the relative risk - such as how much above or below 'background level of risk' the chances of an earthquake are – can be greatly increased. For example, although the actual probability of a smoker getting lung cancer is around 14%, if the risk is expressed as a relative risk, comparing a smoker and a non-smoker's risk of getting lung cancer, the effects of smoking sound much riskier: people are about ten times more likely to get lung cancer if they smoke (Villeneuve and Mao, 1994; Joslyn and LeClerc, 2013). Communicators should be aware of this potentially persuasive power and use it judiciously. Indeed, some relative risks can make things seem very scary indeed. For example, in earthquake aftershock sequences the relative risk of another event might be 100 times higher than it was before the mainshock, yet the absolute risk may still be very low (maybe 1%!). In these instances, it may be better to communicate both the absolute and relative risk together, but care should be taken to ensure that the relative risk is not mistaken for the absolute risk (Visschers *et al.*, 2009).

Finally, the framing – either positive (such as chance of survival, or an earthquake NOT occurring), or negative (such as chance of death, or an earthquake occurring) - can not only affect the magnitude of the numbers being communicated (the chances of something bad NOT happening being a vastly larger probability), but can also affect the perceived risk associated with it (e.g. (Tversky and Kahneman, 1981, 1991; Johnson *et al.*, 1993)). In one experiment on presenting the risks of dying from COVID-19, although presenting the risks in a positive frame (as chances of survival) was liked by participants and reduced their perception of the risk and their worry about it, there was a slight compromise in people's objective comprehension of the numbers involved (A. L. J. Freeman, Kerr, *et al.*, 2020).

4.1.2. Putting a number into context

One of the difficulties in processing these small numbers, particularly for risks that are as rarely experienced as these low likelihood events usually are, is attaching meaning to the number. If there is a 1/10,000 chance of a magnitude M7 earthquake event occurring in your area, and you have never experienced an earthquake before and have no sense of their underlying frequency, variation in size and severity, how can you make a judgement about how that probability may affect you, or a decision about what actions to take on the basis of that information? One tool that risk communicators suggest for aiding with comprehension of unfamiliar risks such as large-scale earthquakes is the use of comparator risks. Comparisons are thought to put risks in psychological perspective by providing a kind of "conceptual yardstick" (Covello, 1991). This is thought to improve understanding of risk magnitudes and be more intuitively meaningful than absolute numerical probabilities by allowing less familiar risks to be compared with those that are better known (Fischhoff *et al.*, 1978; Wilson and Crouch, 1987; Covello, Sandman and Slovic, 1988; Keller, Siegrist and Gutscher, 2006). However, caution needs to be applied when making risk comparisons: in addition to the content of the comparisons (e.g. which comparator risks are chosen), context (e.g. is there an adversarial or contentious context to the communication) should also be considered an important component in designing the comparisons (Covello, Sandman and Slovic, 1988; Roth *et al.*, 1990; Slovic, Kraus and Covello, 1990).

(A. L. J. Freeman, Kerr, *et al.*, 2020) found that comparator risks in and of themselves were helpful to people when trying to understand their personal risk from COVID-19, but a graphical aid called a risk ladder, which shows the positions of comparator risks along a visual scale, is also often used. There is evidence that people are good at intuiting relative risks, even if the probabilities they attach to each specific risk can vary by large magnitudes (Persoskie and Downs, 2015). Indeed when people are asked to judge a variety of risks on different scales, the same ordering between the different risks emerges (although the attached numerical values vary greatly!) (Fischhoff and MacGregor, 1983). Risk ladders were developed to try to make use of this consistency in relative risk judgements to aid communication of the likelihood of less familiar risks (Persoskie and Downs, 2015). They have been shown to be an effective way to communicate levels of risk of such less familiar (often low probability) risks, with participants able to intuit risk levels depending upon the visual position of the risk on the scale (Sandman, Weinstein and Miller, 1994; Siegrist, Orlow and Keller, 2008).

The selection of comparator risk, and thus where the risk to be communicated sits on the visual risk ladder scale, are likely to influence people’s perception of the likelihood of that risk. By choosing risks that are substantially more likely than the low likelihood risk, it is possible to minimise people’s perception of the risk, just as choosing many low likelihood risks, the majority of which are lower in likelihood than the risk to be communicated, can enhance people’s perception of the risk (Sandman, Weinstein and Miller, 1994; Siegrist, Orlow and Keller, 2008). The choice between logarithmic and a linear scale could also make a difference. Although it can be very difficult to display risks of varying orders of magnitude on a linear scale, (A. L. J. Freeman, Kerr, *et al.*, 2020) found that a logarithmic scale can be less trusted than a linear one, although there are logarithmic scales in regular use in medicine, such as the Paling Perspective Scale (Paling, 2003).

4.1.3. Can we use words instead of numbers?

There has been considerable research on attempts to use verbal rather than numerical expressions of likelihood and severity. Verbal probability expressions are thought to be more natural for people to produce and easier for them to understand (Budescu & Wallsten, 1987), however it has been shown that there can be substantial variation in how people interpret such expressions - the specific likelihood that one person associates with the phrase “unlikely” can be wildly different between individuals (e.g. Budescu & Wallsten, 1985; Brun & Teigen, 1988) and cultures (e.g. (Harris *et al.*, 2013)). The same is true of verbal expressions to communicate the severity of the impact, where not only do different people have a different interpretation of the severity, but people also view the probability of an event as being greater than it is when the severity of its impact is high (e.g. (Weber and Hilton, 1990; De Bruin *et al.*, 2000; Harris and Corner, 2011).

Several studies have demonstrated that using numerical and verbal (e.g. likely, unlikely) *together* in communications of probabilistic forecasts can increase the level of differentiation between the various terms, and increase consistency in their interpretation (Witteman and Renooij, 2003; Patt and Dessai, 2005; Budescu, Broomell and Por, 2009; Budescu, Por and Broomell, 2012). It has been argued that the way that people react psychologically to numbers and words is different, with words eliciting a more emotional response, and hence that adding a verbal descriptor of the uncertainty alongside the numbers can help people respond (Windschitl and Wells, 1996). (Budescu *et al.*, 2014) demonstrated that using such verbal-numerical formats increased the alignment between the IPCC’s communication of likelihoods of various climate change impacts and the audience's interpretation of them, replicating this effect across 24 countries. However, in a study examining the effects of four types of probability expressions: verbal (e.g. unlikely); numerical (e.g. 20%) and two expressions combining the two but in different orders (e.g. unlikely [20% likelihood]; 20% likelihood [unlikely]), (Jenkins, Harris and Lark, 2018) cautioned against blanket usage of combined verbal-numerical expressions, suggesting that such combinatorial approaches may be subject to an extremity effect (people interpreting the verbal terms to mean a probability outside that of the numerical range indicated) that numerical-only statements are less subject to. It should also be noted that numerical expressions can also be interpreted differently depending on an individual's prior beliefs about the base rate occurrence of the event in question e.g. (Windschitl and Weber, 1999).

It is important for communicators to be aware of the potential impacts of all these different ways of communicating the same information, else the interpretation by the audience might be substantially different from that which was intended.

4.2. The challenge of dynamically varying risks

There is a lot of information to get across when it comes to communicating dynamically varying risks, and this means their communication may be particularly prone to user cognitive overload and the influence of biases discussed in earlier sections. These can be reduced by careful design of communications that use simple, familiar designs and make use of visualisations as an aid (Eppler and Mengis, 2004; Tan *et al.*, 2020). Indeed a well-designed visualisation (including maps) can attract and retain users' attention, provide a concise summary of data and even reveal hidden patterns in data (Lipkus and Hollands, 1999; Tufte, 2001; Smerecnik *et al.*, 2010; Spiegelhalter, Pearson and Short, 2011).

4.2.1. How graphics can help

> **Types of visual display**
>
> Visual-spatial displays can be what is called ‘iconic’, ‘relational’ or ‘hybrid’ (Hegarty, 2011).
>
> Iconic displays are representations of objects that are actual visual-spatial objects themselves, such as technical diagrams of a machine, a road map, or a map of the London underground. They are often simplified by comparison to the real object(s), and as such can provide potentially misleading distortions of reality, such as missing out certain details, or distorting any distance information depicted (Hegarty, 2011).
>
> Relational displays are those that represent abstract relations between things that are not themselves spatial and/or physically tangible, such as a scatter plot to represent the correlation between height and weight, or a tree diagram to represent phylogenetic relationships between species (Hegarty, 2011).
>
> Visual-spatial displays can be a hybrid of these two, in that they represent actual real world entities in addition to more abstract properties, such as a map of Europe (iconic display) that shows temperature or wind speed as a gradient of colours overlaid (relational display) (Hegarty, 2011).
>
> Each of these type of display can be made more complex by the addition of different parameters, such as different sections through a brain MRI, interactivity to allow rotation, zoom, the adding of layers or pop out text to provide additional information upon click, or a series of panels or animated maps depicting change through time (Hegarty, 2011); (Tversky, Morrison and Betrancourt, 2002).

Visualisations or graphical depictions of information can reduce cognitive load in several ways. Firstly, they provide external storage of detailed information, allowing internal representations to be sparse, rather than a detailed replica of the information being communicated (Hegarty, 2011; Pylyshyn 2003; Scaife & Rogers 1996; Zhang & Norman, 1994). Secondly, they provide spatial organisation of information (Larkin & Simon, 1987), facilitating visual search and mental integration (Hegarty, 2011). Thirdly, they can map non-visual data onto visual variables, allowing patterns or “emergent features” to be detected by the visual system that are more salient (i.e. attract more attention) than the individual data themselves (Pomerantz & Pristach, 1989), so offloading cognitive processes onto perceptual ones (Scaife & Rogers, 1996). In turn this process can facilitate comprehension by reducing the number of inferences it is possible to make from the represented data by constraining properties of a visualisation to rules of logic, for example if object A is visualised within object B in one panel of a diagram, and object B within object C in another panel, it is logically impossible that object A be bigger than object C (Scaife & Rogers, 1996; Hegarty, 2011). Finally, in a similar vein, interactive visualisations can offload cognitive processes onto action, such that internal computations are instead replaced by external manipulations of the visualisation (Card et al. 1999) for example by allowing people to change the orientation of an object without having to rotate it mentally, or allowing choice in filtering of which information is displayed (Kirsch & Maglio, 1994; Schneiderman, 1994; Hegarty, 2011).

4.2.2. Dashboards

Dashboards are a graphical way to bring dynamic data together visually in such a way as to help people recognise patterns and anomalies quickly and easily (Brath and Peters, 2004; Few, 2006). Although inspired by the dashboards of cars, trains and planes they are designed to help people navigate dynamic data rather than a moving landscape. A classic early use was for stock market displays, but they are now used across many business and data-management situations. City dashboards are a relatively new phenomenon: publicly displayed graphical dashboards that display constantly streaming data about the local environment from both sensors and official information and crowd-sourced data (Stehle and Kitchin, 2020). Because they are designed for a public audience and change over time in a geographical area, their design is perhaps of particular relevance to displays of seismic information. The audience are not simply passive recipients of hazard forecast communication; increasingly, particularly due to the increase in online content access and social media, they play an active role in its creation, evolution and dissemination and so may contribute crowd-sourced data to any communications (Hyvärinen and Saltikoff, 2010; Hughes *et al.*, 2014; Morss *et al.*, 2017; McBride *et al.*, 2019).

The principles of dashboard design are like those of any other communication: start by working with the audience to discover what information is important to their decision-making and then iteratively design and evaluate to improve them. However, there are some other key principles once the right information has been selected (Few, 2006). Firstly, putting all the information onto one screen (without the need for scrolling) to allow easy and rapid comparisons of the different displays. Secondly, giving the information enough context (e.g. displaying time series where it is important to look at relative change through time, or geographical information where it is important to compare values spatially), and interpretation (e.g. visually indicating high and low values, important thresholds etc). Thirdly, reducing excessive detail or precision: every piece of information that is not important to making the decision or seeing the pattern that is important (e.g. excess decimal places, unnecessary axis space) reduces the visual space and the cognitive space of the audiences for the important information. Fourthly, carefully choosing the right forms to represent the data – forms that both highlight the salient information (and the change being looked for) and that take up the least visual space. Consistent use of the same graphical presentations can help easy comprehension as the audience becomes familiar with the graphic. This taps in to the principles of good data visualisation (see below). Finally, arranging the data in the display in a way that helps the user, with the most prominent positions given to the information that is needed first/most quickly/is most important, and using colours consistently.

4.2.3. Graphical representations

There is a vast literature and decades of work on how best to represent data graphically (e.g. (Tufte, 2001; Ware, 2013). The Gestalt principles date to the 1920s (Wertheimer, 1923) and have been elaborated on and built on ever since. We will not review the entire field here!

If communication is to be successful, it must both be easy on cognitive load and must also convey the correct information in a comprehensible way that allows relevant tasks to be completed. Representations of data that are informationally equivalent are not always computationally equivalent (Larkin & Simon, 1987; Hegarty, 2011). Indeed performance on different comprehension tasks can vary widely between different types of display of the same information, such as graph type, choice of variable assignment to the x or y axis, and choice of colour or intensity values (e.g. Hegarty, Canham & Fabrikant, 2010; Peebles & Cheng, 2003; Sanfey & Hastie, 1998; Ye & Wickens, 2001; Simkin & Hastie, 1987), highlighting the need for careful design and evaluation of communications (Hegarty, 2011).

In turn, viewers may fail to encode information relevant to comprehension and task performance if they are distracted by task irrelevant information that the communication makes highly salient (Hegarty, 2011). This not only reduces the efficacy of the communication but also could be considered to be potentially misleading if viewers are guided towards incorrect conclusions.

In addition to these "bottom-up" processes of catching a viewer's visual attention, comprehension and decision making may also be influenced in a "top down" way by domain knowledge (Hegarty et al. 2010). Knowledge and/or skill in a domain improves viewers' ability to ignore irrelevant information and focus on that which is task-relevant (Haider & Frensch, 1996; 1999), whilst non-expert users are more likely to have their attention captured by those features of the display that are most salient (Lowe, 1993; 1994; 1996). As such, expert audiences may comprehend communicated information in a different way from lay-audiences. As aforementioned, the role of emotions, experience and worldviews can also affect the way in which information is interpreted and decisions are made off the back off it, adding variation and complexity in audience responses to a communication.

Knowing what an audience's (and individual's) relevant tasks, knowledge base and socio-cultural norms are however, is not always obvious. As discussed earlier, one first needs to understand who the audiences for their communications are, what types of knowledge they have about the system being communicated, what decisions these audiences are using the communicated information to inform, and what information they see as being most relevant to facilitate that decision making.

Understanding of visualisations can also be challenged if people need to first learn the meaning of different components of a visualisation (e.g. axes), known as "graph schema" (Pinker, 1990; Ratwani and Trafton, 2008) or what task-relevant interactions with the visualisation are possible (e.g. rotation), known as meta-representational competence (DiSessa, 1994). Thus there may be some advantage of using formats that people are already familiar with, for example using intuitive colours such as blue for water, or red for danger and paler colours to indicate areas which are safer (Bostrom, Anselin and Farris, 2008; Hagemeier-Klose and Wagner, 2009; Hegarty, 2011; Thompson, Lindsay and Gaillard, 2015) or using differences in symbol size to indicate different magnitudes (e.g. stronger, larger) (Gaspar-Escribano and Iturrioz, 2011), although one should be aware of cross-cultural variability in these norms. In turn, other forms of communication, for example the use of narratives or scenarios to communicate risk, can add depth and tone to communications that might not be possible using a visualisation. However, these should not be employed blindly, as research in some areas (e.g. healthcare) has indicated how complex the effects of narrative are on people's emotions and decision-making (Bekker *et al.*, 2013). Thus careful, audience-informed design of communications and evaluation in contexts relevant to that audience is essential. We therefore review what has been empirically tested in terms of visualisation within each chapter of this report, with a particular concentration on testing of visualisations that may be relevant to seismic forecasts.

4.2.4. Icons

Icons are graphical representations designed to remove the need for more space-consuming and cognitively-intensive text (Ware, 2013). Pictograms – 'human-recognizable objects' - are often used as they are memorable and easily understood (Borkin *et al.*, 2016). Most, however, are not simple pictograms, but are metaphors, representing a concept only metaphorically related to the object depicted itself. Both the clarity of the pictorial image itself (e.g. a waste paper bin), and the clarity of the metaphor that links that image to the intended meaning (e.g. deletion of digital files) to the specific audience is critical (Carroll, Mack and Kellogg, 1988; Gaissmaier *et al.*, 2012; Borkin *et al.*, 2013, 2016). If people don't easily understand what physical object the image is supposed to represent, or don't easily understand what concept that physical object is a metaphor for, the icon will fail. Icons can also be 'layered', combining shapes with indications of magnitude (Zender, 2006). There are many principles of good icon use (see (Forsythe, 2011) for a review), but as with other communications the key is co-design and testing with the intended audience.

4.2.5. Visuo-spatial displays: Maps

One of the key properties of an effective map display is that it makes information that is relevant to the user's task perceptually salient (Bertin, 1983; Kosslyn, 1989; B. D. Dent, 1999; Hegarty, Canham and Fabrikant, 2010). Cognitive scientists go some way towards guiding the viewer towards which information is relevant to their particular task by attempting to manipulate the salience of conceptual objects, although upon evaluation the effects of visual salience on task performance have been mixed (e.g. (Fabrikant, Hespanha and Hegarty, 2010; Hegarty, Canham and Fabrikant, 2010)).

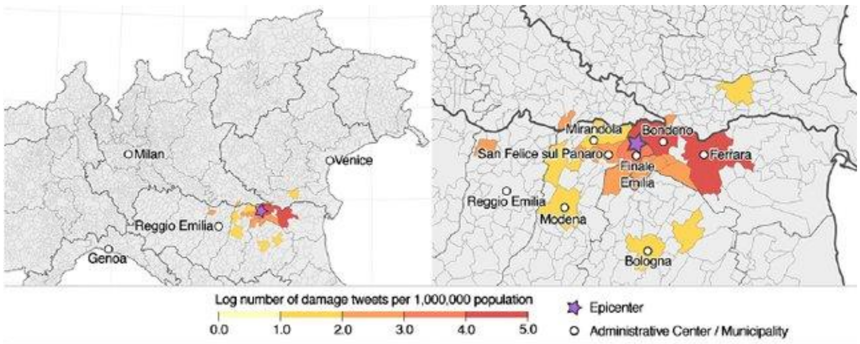
Intuitively we might think maps are limited to displaying geographically varying information, however they can also be useful for displaying temporally varying information too, not just by animation but also by representing relative rather than absolute values i.e. change.

Maps not only allow the display of objects at a scale we would not normally encounter (e.g. a whole country or continent), they also allow multiple conceptual variables to be depicted at once (e.g. temperature, precipitation, pressure and relative changes in a variety of variables) by using different visual objects (Hegarty et al. 2010). Again careful design is essential however; maps are commonly used to communicate about natural hazards, yet they are often misunderstood (Thompson, Lindsay and Gaillard, 2015; Marti, Stauffacher and Wiemer, 2019).

What information to display: continuous versus categorical

(Gaspar-Escribano and Iturrioz, 2011) note that key to good map design is not only careful selection of the visual aspects of the design itself, but also of which and how many parameters to be depicted in the first place. In turn, those parameters and design features that are suitable for one audience may not be suitable for another. They suggest that the first consideration about each parameter to be represented is whether it follows a continuous (e.g. continuous gradient in temperature) or discrete (e.g. different countries on a map) distribution, as this will determine how it might be represented graphically.

According to cartographic principles, discrete data are themselves represented differently depending on whether they represent absolute or relative values (Robinson *et al.*, 1995; B.D. Dent, 1999). Absolute values are typically represented by proportional (or graduated) circles, which are single symbols (often circles) whose size varies according to the value to be represented, although proportional circles can also be used to represent relative amounts (Gaspar-Escribano and Iturrioz, 2011). This gradation in size tunes into an intuitive perception that bigger symbols represent higher (larger, stronger etc) values. However, perceptual biases mean that people find it very hard to accurately assess areas and volumes (where they need to take into account change in more than one dimension) as compared to lengths of lines (where they only need to take into account a single dimension)(Lipkus and Hollands, 1999). This means that representing absolute (or even relative) risks by area of circles is not likely to lead to accurate perceptions.



A chloropleth map for the Emilia 2012 earthquake showing the distribution of tweets reporting damage, from (Cresci et al., 2015). This actually displays absolute values, unlike strict cartographic principles.

Relative values can additionally be represented using chloropleth maps, which use a predefined colour scheme to colour discrete geographic units. The decision about the number of categories and size of class intervals is important for any discrete data if the categories themselves are artificially imposed; several maps representing the same data can look very different if they use different interval sizes and numbers of categories (Evans, 1977; Cauvin, Escobar and Serradji, 2010; Gaspar-Escribano and Iturrioz, 2011).

Continuous data can be represented using a continuous gradient of colour. Although (Gaspar-Escribano and Iturrioz, 2011) suggest isolines can be useful for representing continuous data, smooth gradients were liked by participants in (Becker *et al.*, 2019)'s work on earthquake hazard maps as they avoided artificial boundaries. Whilst less discrete than the coloured polygons that might be used on a chloropleth map, isolines, even if represented very densely, are often still discrete categories, for example lines connecting points of equal temperature across a map.

Artificially imposing categories on continuous data deserves a little more discussion. Since probabilistic hazard assessments have been judged by some to be difficult for lay people to understand (Mileti *et al.*, 2004), it has been suggested that it may be better to represent data for this audience as discrete categories on a map, such as high, medium or low (Gaspar-Escribano and Iturrioz, 2011). While categorisation can be a useful way of simplifying complex data, it can't be assumed that comprehension and decision making quality will be enhanced. Categorisation can make data appear more certain and discrete than they actually are. As discussed in more depth later in this report, there is evidence from a variety of disciplines that uncertainty can lead to higher quality decision making if presented in the right way (Roulston *et al.*, 2006; Joslyn *et al.*, 2007; Morss *et al.*, 2008; Nadav-Greenberg and Joslyn, 2009). In turn, if the categories are given verbal descriptions (e.g. 'high risk') without any numerical definition, interpretation of their meaning can differ wildly between individuals (as previously discussed). Thus any decision to categorise data should be carefully considered, ideally with the intended audience (e.g. for some expert audiences, certain threshold values may have particular significance, e.g.(Becker *et al.*, 2019)) and its effects evaluated, and at the very least it should be ensured that the categories are attached to specific numeric definitions.

Using colour

Information on a map can be depicted intrinsically by manipulating attributes of what is already depicted (e.g. using brightness, texture, colour and transparency (Bretin, 1981), or animation and extra dimensionality such as making certain points 3D (Gershon, 1998), or extrinsically by adding new objects to the visualisation (e.g. glyphs, arrows, bars or even overlaid graphs) (Howard & MacEachren, 1996; Gershon, 1998; Kinkeldey et al. 2014). Choice of each attribute can have substantial impacts on the map's efficacy. For example high contrast ratios and clear colours improve map understanding (Hagemeier-Klose and Wagner, 2009), with contrast particularly important for people with colour vision deficiencies (Kunz, Grêt-Regamey and Hurni, 2011).

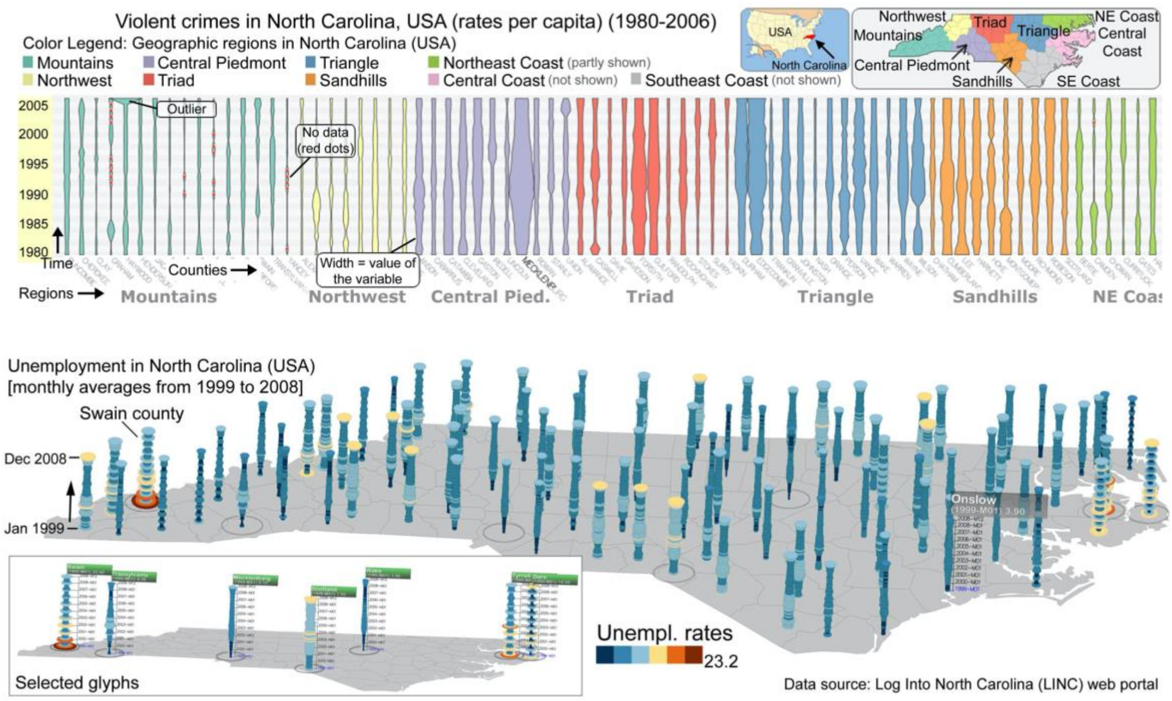
Interpretations of colour are not neutral however. For example, maps depicting the same information but using different colour palettes can be interpreted differently by end users (Thompson, Lindsay and Gaillard, 2015). Furthermore the choice of how to categorise different data values using colour or other attributes affects interpretation. Breaking different subsets of data into different colour coded categories may simplify the representation and make maps easier to understand (Fuchs *et al.*, 2009; Gaspar-Escribano and Iturrioz, 2011; Marti, Stauffacher and Wiemer, 2019), however this can also lead viewers to perceive false dichotomies between the different coloured regions, where in fact the distinction may be much more uncertain (Smith, 2000). A continuous representation of the data (for example by a using continuous transition of colour or hue) may provide a more realistic representation of the data and its variability, although it may be difficult in such representations for users to attribute specific values to individual datapoints or identify small changes between values where the difference in colour is only very slight (Severtson and Vatovec, 2012).

The choice of colour scheme and gradient is critical to avoiding both perceived boundaries where none exist, and perceptual biases based on our human colour perception. It is therefore crucial to be aware of work specifically in this area, such as (Kovesi, 2015; Crameri, Shephard and Heron, 2020). Darker colours are typically associated with higher values, thus a gradient of different shades of the same colour can convey a hierarchical order to data; if several different colours are used it may be harder to infer this relationship (Gaspar-Escribano and Iturrioz, 2011). On top of these perceptual biases, colours can also carry intuitive meaning, such as blue for water, red for danger and paler colours to indicate areas which are safer (Bostrom, Anselin and Farris, 2008; Hagemeier-Klose and Wagner, 2009; Hegarty, 2011; Thompson, Lindsay and Gaillard, 2015). Such meanings can be culturally and context-specific and so the choice of colour must always be made carefully.

4.2.6. Animation & alternatives

Animation is, of course, a way of displaying data intuitively through time, especially when combining both geographical change with temporal change. However, it can bring perceptual difficulties, and must be used carefully (see (Tversky, Morrison and Betrancourt, 2002; Harrower, 2007). One problem that has been noted in particular is change blindness – a decreasing ability of the audience to discriminate change – which has been measured on people viewing animated maps, and which requires careful research and testing of combinations of colours and brightnesses to ensure that users are assisted in identifying key changes (Goldsberry and Battersby, 2009; Cybulski and Medyńska-Gulij, 2018).

An alternative to animation which still provide both spatial and temporal information in an intuitive way is visualising 'glyphs', which represent data at a geographical location but can also encode temporal information (Thakur and Hanson, 2010). See below for examples.



2D and 3D glyphs showing data that changes over both space and time, without animation, from (Thakur and Hanson, 2010).

4.2.7. Interactivity

User-control over visualisations and animations is generally considered to be a huge benefit to understanding (Harrower, 2007).

The optimal design and level of detail for one type of user may be very different from that for another, and focus groups on operational earthquake forecasting comment how they appreciate a range of presentations (Becker *et al.*, 2019), although there is currently a dearth of empirical evaluations about multiple formats and interactive displays. Interactivity allows customisation by the individual user of various aspects of the communication: switching between different formats, drilling down for deeper levels, and changing parameters on maps and graphics such as interval classification, colour scale (e.g. colour deficiency scales), geographical unit definition, and the addition or removal of other visualised parameters (Cartwright, 1997; Miller, 2007; Petersen, 2007).

In some cases, however, non-interactive animated graphics are preferred by users to get an overview, with interactivity only added when they are likely to want more detail (Slocum *et al.*, 2004).

Of course there is always a trade-off between increasing options and interactivity and overloading the user with visual information. There is also something called the 'split attention effect', caused by asking a user to mentally integrate disparate sources of information (Mayer and Chandler, 2001). This can easily be caused by interactive displays, as users are having to learn to both how they are supposed to interact with the display and simultaneously take in the information being presented to them. As with everything, it is necessary to test individual communications with their intended users.

4.3. The challenge of high uncertainty

Many scientists and policy makers have concerns about communicating uncertainty, fearing it may cause misunderstanding, bias interpretations, undermine perceptions of trustworthiness or credibility, evoke negative emotions, overwhelm a viewer's attention, or undermine the quality of decision making (Fischhoff, 2012; Manski, 2018; Dryhurst, van der Bles, *et al.*, 2020; Hullman, 2020; van der Bles *et al.*, 2020) Nevertheless, some suggest that there may be positive effects of communicating uncertainty, suggesting that communicating uncertainty inherent to scientific information may build trust in institutions through demonstrating trustworthiness (O'Neill, 2014).

Of course, we have already discussed the use of probabilistic terminology (either in numerical form, or as both words and numbers), which seems to be broadly accepted by the public in the context of weather forecasting, at least, as there appears to be an implicit acceptance of aleatory uncertainty when talking about the future (Morss *et al.*, 2008; Joslyn and Savelli, 2010).

Several studies have begun to evaluate different formats of communicating epistemic and aleatory uncertainty, and to examine for possible negative effects. Many of these have looked at the effects of communication of uncertainty on perceptions of trust. Some demonstrated positive and negative effects on trust (e.g. (Johnson and Slovic, 1995, 1998)), and others have shown that effects break down according to particular audience characteristics such as education level (Schapira, Nattinger and McHorney, 2001), numerical ability (e.g. (Dieckmann, Peters and Gregory, 2015)), and prior beliefs about a topic, particularly when contested or culturally relevant (e.g. (Rabinovich and Morton, 2012; Dieckmann *et al.*, 2017)). However elsewhere studies have demonstrated no negative effects of communicating uncertainty on perceived trust (Kuhn, 2000; Han, Klein and Arora, 2011). Others still have shown positive effects, where communicating uncertainty is actually associated with higher levels of trust, when there is feedback on the forecast's accuracy (Joslyn and LeClerc, 2012).

In a comprehensive study on members of the public (including a field experiment on the BBC website) examining the effects of communicating uncertainty on the trust in facts and numbers, (van der Bles *et al.*, 2020) tested the effects of using words and numerical ranges to communicate uncertainty about topics such as climate change and immigration. They demonstrated that whilst some verbal expressions of uncertainty can undermine perceptions of trust, communicating uncertainty numerically only had a very small impact on trust in the numbers, and none on trust in the communicators.

Several studies have examined the efficacy of different types of visual communications for serving audience comprehension. There is evidence that visual depictions of mean and error that use gradient plots and violin plots may yield interpretations that are more statistically valid than similar communications using bar charts with error bars (Ibrekk and Morgan, 1987; Newman and Scholl, 2012; Correll and Gleicher, 2014). (Gschwandtner *et al.*, 2016) have studied the same formats when used to represent temporal uncertainty along a timeline. They found that participants disliked the gradient and violin plots, but gradient plots best represented the statistical uncertainty. Other studies have shown that mean and error summary displays can often be misinterpreted, by both the public and experts (Belia et al. 2005; Newman & Scholl 2012; Savelli & Joslyn, 2013).

Another approach to visual communication of uncertainty is an ensemble display, commonly used in epidemiological, weather and storm forecasting (e.g. hurricane track ‘spaghetti plots’ for geographical uncertainty on maps), and summary versions of these (such as ‘cones of uncertainty’ on maps and fan plots around line graphs). There has been extensive work on hurricane uncertainty (e.g. (Ruginski et al. 2016; Padilla et al. 2017)) revealing that both the summary ‘cones’ and the ensemble ‘spaghetti plots’ can lead to misinterpretations, and work is ongoing to decrease these through redesigns (Padilla, Creem-Regehr and Thompson, 2020). We review this work in more detail later in this report.

(Dryhurst, van der Bles, *et al.*, 2020) examined the effects of communicating uncertainty around line plots in forms such as fan charts or gradient plots. Using data series about COVID-19, migration, unemployment and election polls, they demonstrated that this uncertainty communication did not generally have any effect on audience comprehension, nor on their trust in the data or data providers. Encouragingly, the study also showed that uncertainty may increase people’s nuance in their interpretation of trend lines.

Another type of uncertainty ensemble display in animated form is a hypothetical outcome plot (HOP), and such visualisations have been shown to perform better than interval-style visualisations of error bars and violin plots when people are making judgements about multiple quantities, potentially improving ability to estimate outcome variability and interpret effect sizes. (Hullman, Resnick and Adar, 2015; Hofman, Goldstein and Hullman, 2020).

Alongside the quantified/quantifiable uncertainty (such as the probabilities or the ensemble of models) is the unquantifiable uncertainty – the quality of the underlying evidence that led to the model. This encompasses so much uncertainty in the field of seismic forecasting, (a relatively young field, working on very incomplete data, with many theoretical assumptions underlying the modelling) that it is particularly important to try to communicate it. It is perhaps this kind of uncertainty – and the difficulty of communicating it – that is of most concern to forecasters.

Seasonal climate forecasters in the US state the ‘skill’ level (a rating of how well the forecast has performed over historical time) of their forecasts alongside them (Barnston, He and Unger, 2000). Researchers in healthcare do a qualitative, subjective rating of the quality of evidence and communicate it via a 1-5 scale (Oxman *et al.*, 2020; Santesso *et al.*, 2020), and others in different fields have similar kinds of subjective rating systems (Puttick, 2018).

Unfortunately, work on evaluating the effects of these attempts to communicate underlying quality of evidence is in its infancy. Work (Schneider, Freeman and van der Linden, 2021) has shown how crucial such information is in people’s decision-making, and that the assumptions from public audiences are often that scientific evidence is of higher certainty than it actually is, so it will be particularly critical to work out how best to communicate the low certainties that seismic forecasters have in their probabilistic forecasts.

4.4. The challenge of misinformation

Research into how best to combat misinformation suggests that the problem isn’t a simple one. Indeed, misinformation can often be immune to post-hoc correction or retraction. Under such circumstances people may hold on to the misinformation they have received and integrated into their belief system, known as the continued influence effect (Cook, Ecker and Lewandowsky, 2015; Chan *et al.*, 2017; Walter and Tukachinsky, 2020) There had also been concern that correction of misinformation may result in a “backfire effect” whereby the repeating of the misinformative statement during correction actually reinforces the strength of belief in that misinformation (Lewandowsky, Ullrich K.H. Ecker, *et al.*, 2012), resulting in recommendations to communicators that they should try not to repeat misinformative statements in any correction attempts (Lewandowsky, Ullrich K.H. Ecker, *et al.*, 2012; Peter and Koch, 2016; Schwarz, Newman and Leach, 2016). However, there is little evidence for the backfire effect (Ecker, Lewandowsky and Chadwick, 2020), and some studies suggest that repeating a piece of misinformation alongside the correction is actually more effective than a correction that did not repeat it (Cameron *et al.*, 2013; Ecker, Hogan and Lewandowsky, 2017) thus even if correction does not work, repeating the misinformation content with the correction shouldn’t have a negative influence on the strength of belief in the misinformation (Ecker, Lewandowsky and Chadwick, 2020).

This research was reinforced by a study by (Whitney, Lindell and Nguyen, 2004) in the earthquake literature that demonstrated that corrections of myths about earthquakes (such as that they can be predicted) were more effective when they used an “Earthquake myths versus facts” format than when they used a format that detailed earthquake facts alone. In further encouraging research, (Ecker, Lewandowsky and Chadwick, 2020) found no negative effect of a correction that contained reference to a misinformation statement that was novel to the reader i.e. corrections may also be useful prior to exposure to the misinformation in the first place, and not just post-hoc.

It is worth noting here that this research may have some relevance to post-alert messaging after warnings have been issued. Rapid communications of corrections or explanations by alert issuers if the alert turns out to be a false alarm or needs updating in any way has been highlighted by several authors to be an important component of engendering trust in organisations managing the crisis (Covello, 2003; Seeger, 2006; McBride *et al.*, 2020). It is encouraging that such post-hoc communications and corrections may not reinforce beliefs in the original warning that was issued, and thus may serve their purpose of keeping the population informed and engendering trust. Such corrections by official sources have been shown to be highly effective in debunking misinformation around natural disasters (Takayasu *et al.*, 2015; Hunt, Wang and Zhuang, 2020).

In a slightly different approach, an area of research that shows great promise when it comes to reducing the influence of misinformation is the idea of inoculating against it. Inoculation theory was originally conceived of by (McGuire, 1970) in an attempt to "vaccinate" against propaganda. Just as an immunological vaccine may pre-emptively confer protection against a particular pathogen, inoculation theory argues that by pre-emptively presenting someone with a weakened version of a misleading piece of information, immunity to the actual misinformation may be conferred by the weakened version triggering a thought process akin to a cultivation of "mental antibodies" (Compton, 2013; van der Linden and Roozenbeek, 2020). Evidence has accrued that inoculation approaches can confer resistance to misinformation about health (Compton, Jackson and Dimmock, 2016), politics (Pfau *et al.*, 2001) and even highly contested issues such as climate change and immigration, where people often have strongly held or ideologically-informed prior beliefs (Cook, Lewandowsky and Ecker, 2017b; van der Linden *et al.*, 2017b; Maertens, Anseel and van der Linden, 2020; van der Linden, Panagopoulos and Roozenbeek, 2020).

One possible weakness with these earlier inoculation attempts is that they rely on passive reading of information in order to confer the desired resistance, whereas active and experiential processes are much more conducive to learning. In turn, there is the issue of how to scale inoculation theory; it would not be possible to pre-emptively refute every individual fake news story that ever came along (van der Linden and Roozenbeek, 2020). A solution developed by (Roozenbeek and van der Linden, 2019a) (Roozenbeek and van der Linden, 2019b) is using gamification; the authors developed a series of games that allow participants to play the role of a fake news producer or a twitter user, charged with attracting followers by sharing fake news online. Players are exposed to weakened doses of fake news by having them actively generate their own content in order to gain followers and win the game. The "Bad News" game focuses on those strategies most common to many fake news stories, such as impersonating people online, building echo chambers and using emotional language in order to confer broader brush "immunity" that that which would be conferred by earlier passive and topic specific approaches. (Roozenbeek and van der Linden, 2019a) integrated a pre-post survey test into the game, testing people's ability to identify fake news items before and after playing. They found that the game significantly reduced players beliefs in several of the key fake news strategies. A similar game has been developed by (Basol, Roozenbeek and van der Linden, 2020) to attempt to combat misinformation about COVID-19 called "Go Viral"; once enough data has been collected, the researchers will run similar analyses to ascertain whether this game is successful in conferring resistance to misinformation about COVID-19.

5. Best practice in communicating weather and climate forecasts

Weather forecasts have a long and venerable history, so forecast professionals have developed a solid understanding of their different audiences through research and experience. Although some of their communications suffer from legacy issues (it's difficult to change something that everyone has become used to), they have developed many ways to overcome the problems of communicating uncertain forecasts, over wide geographical areas, that constantly change through time. Long-term climate communicators have also gained a lot of experience in dealing with misinformation.

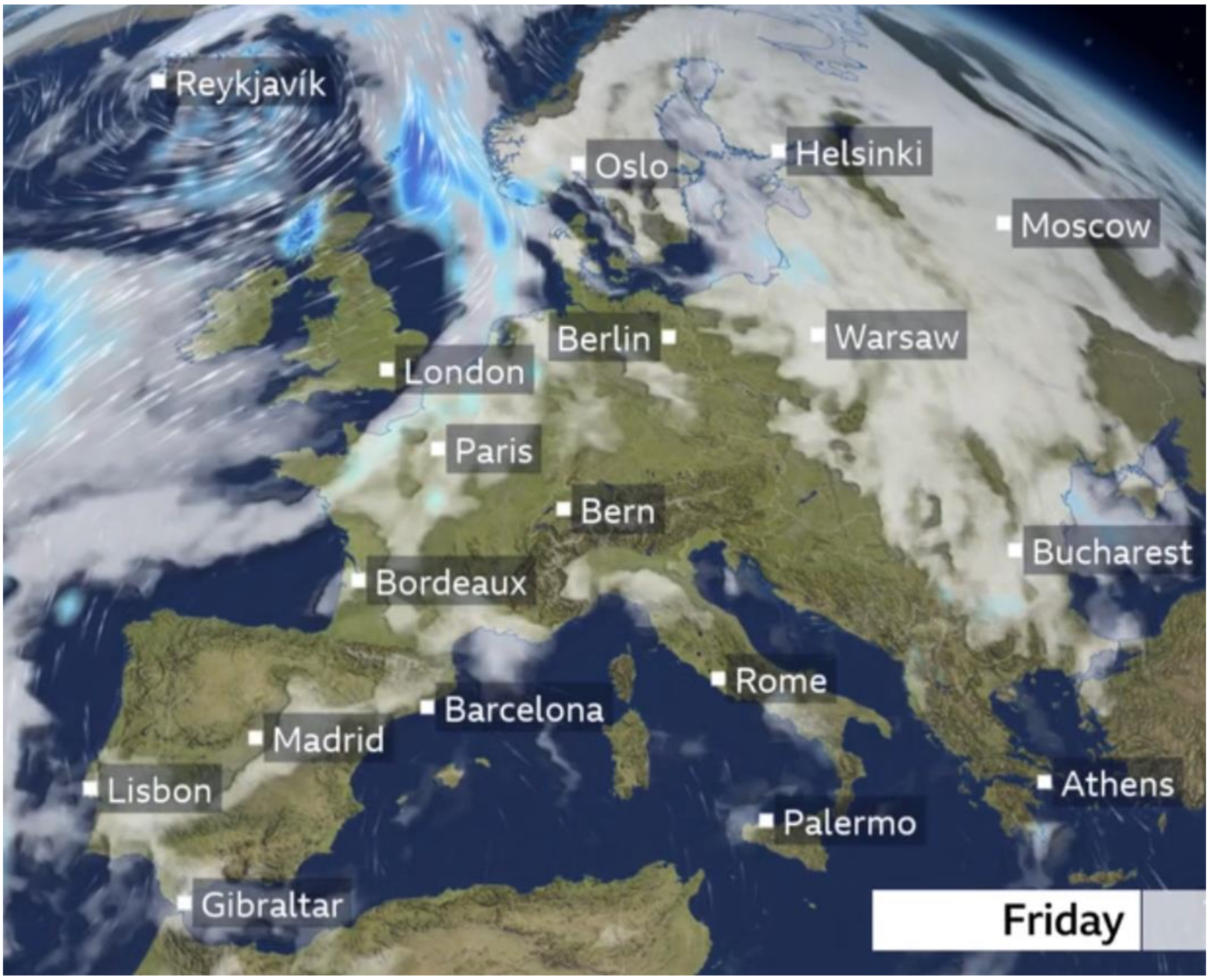
In this review we have separated everyday weather and climate forecasts from storm forecasts in particular, which have a different focus.

5.1. What is being done in practice

Weather and climate services have seen rapid development in recent years, in part due to technological developments in meteorological observation and modelling, and in telecommunications in general (Deconinck *et al.*, 2017; Nkiaka *et al.*, 2019). (Vaughan, Dessai and Hewitt, 2018) reviewed over 100 climate services and found that a typical service was produced by a research institute, often in conjunction with a national meteorological institute, and operated at a national scale to provide seasonal climate information (sometimes paired with weather forecasts or longer term climate information) communicated online, mostly to agricultural decision makers. The authors note however, that there was a lack of empirical evaluation of the effectiveness of communications by existing climate services.

5.1.1. Communicating spatially dynamic information

Everyday weather forecasts are often designed to show the weather pattern over a geographically broad area. This not only allows the forecast to be relevant to a large audience – useful for a broadcast or geographically-widely-distributed medium – but also allows the audiences to get an understanding of the prevailing weather pattern (and hence to develop their own feelings about the certainty or uncertainty of a forecast in one particular location).

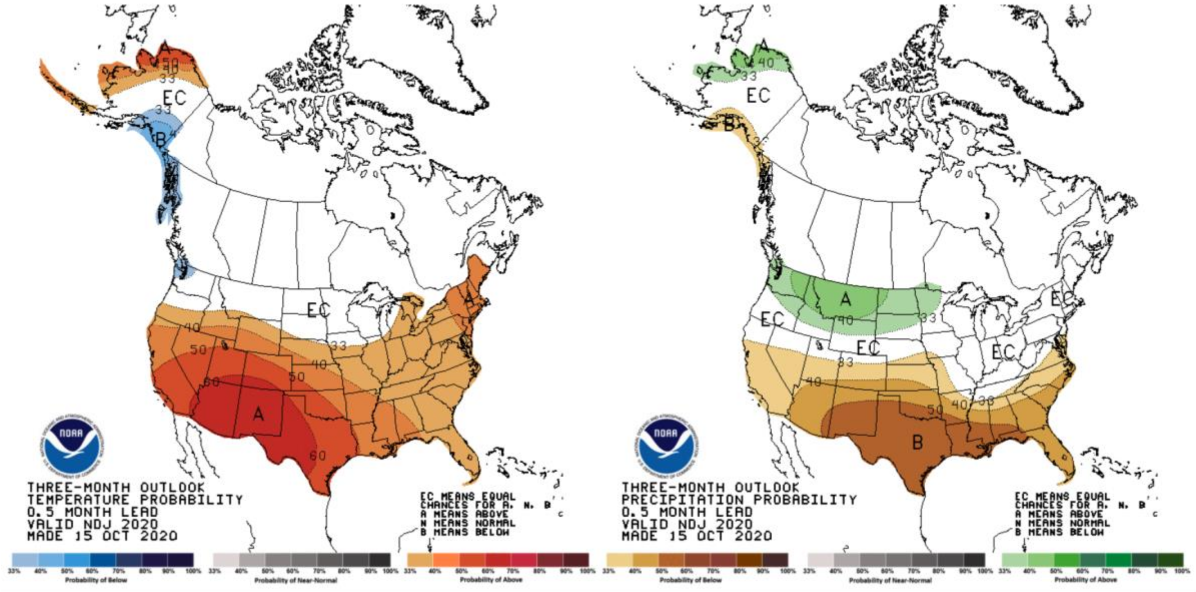


A screenshot of the UK Met Office's European animated forecast

As is familiar to most, weather forecasts often use a map (or series of maps), each showing an average forecast for a single timepoint (such as a day) at a variety of locations across the map. There is usually little probabilistic information in this type of display. One challenge is choosing the resolution of the forecast that suits the audience (or the uncertainty in the forecast itself). This is a problem more acute in storm forecasting, and is covered in that chapter.

Of course, where animation is possible, dynamic change across the geographic area through time can be illustrated by showing multiple maps one after the other.

Seasonal climate information, however, is often communicated in terms of relative risks. For example, the US Climate Prediction Center, which provide seasonal forecasting (mainly for agriculture), use colours and isobars to illustrate their forecasted temperature and precipitation deviations from 'normal' for coming seasons.



NOAA Climate Prediction Center's seasonal forecast, used by agricultural producers and water supply professionals showing the predicted relative difference from seasonal 'normal' values over a 3-month period (NDJ = November, December, January).

These seasonal forecast maps cannot easily display uncertainty or detailed quantitative information. For that, the Center produces 'Probability of Exceedance' data, either as curves or via an interactive calculator. The maps are also accompanied by a text description, including text designed for a non-expert audience (see below).

Prognostic Discussion for Long-Lead Seasonal Outlooks
NWS Climate Prediction Center College Park MD
830 AM EDT Thu Oct 15 2020

SUMMARY OF THE OUTLOOK FOR NON-TECHNICAL USERS

La Nina conditions are present across the equatorial Pacific Ocean, as represented in current oceanic and atmospheric observations. La Nina conditions are likely to continue through the Northern Hemisphere winter and into Spring 2021.

The November-December-January (NDJ) 2020-2021 temperature outlook favors above-normal seasonal mean temperatures for a majority of the CONUS and for northern and western parts of Alaska. The greatest probabilities (larger than 60 percent) are forecast for parts of the Southwest. Below-normal temperatures are most likely for areas of southeast Alaska, the Alaska Panhandle and parts of the far Pacific Northwest.

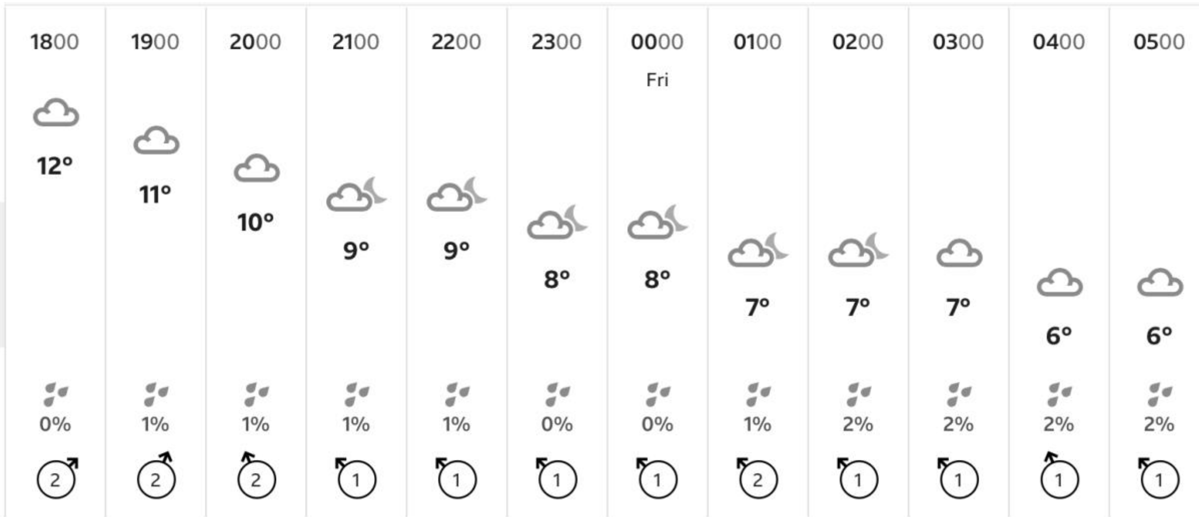
The NDJ 2020-2021 precipitation outlook depicts enhanced odds for above-normal seasonal total precipitation amounts for Alaska and parts of the Pacific Northwest, northern Rockies and northern Great Plains. Below-normal precipitation is most likely for much of California (slight tilt in the odds), stretching eastward to include the Southwest, south-central Great Plains, lower Mississippi Valley and Southeast.

Equal-chances (EC) are forecast for areas where probabilities for each category of seasonal mean temperatures or seasonal total precipitation amounts are favored to be similar to climatological probabilities.

BASIS AND SUMMARY OF THE CURRENT LONG-LEAD OUTLOOKS
Note: For Graphical Displays of the Forecast Tools Discussed Below See:
http://www.cpc.ncep.noaa.gov/products/predictions/90day/tools/briefing

5.1.2. Communicating temporally dynamic information

As mentioned above, it is possible to communicate dynamic geographical information to some extent by simply animating maps, but for audiences only interested in the forecast for a particular location, apps and other very localised information sources (e.g. a local town newspaper) can dispense with the need to cover a wide geographic area and instead concentrate on giving more precise temporal information. This can be given without uncertainty (in a deterministic format), or – increasingly commonly – given in a probabilistic form. A study in 2014, stopping public on the street in the UK, showed that these 'narrow' weather forecasts were the preferred format, particularly for the under-40s (Abraham *et al.*, 2015).



An example of a 'narrow' weather forecast from the UK's Met Office

5.1.3. Communicating uncertain information

As with all forecasts, weather and climate forecasts are inherently uncertain in nature. However, they are often (at least historically) communicated in a deterministic way (e.g. through icons indicating rain). Since these predictions are 'reality-checked' regularly by the audience, it is particularly important that the audience understand the uncertain nature of the forecast.

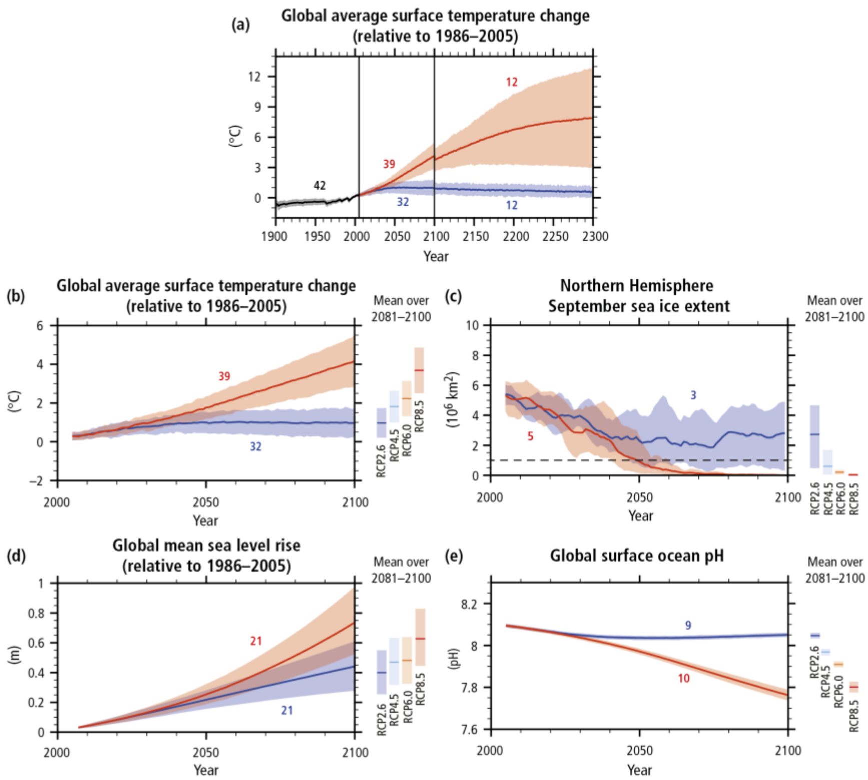
One of the major challenges is thus how to communicate uncertainty in a comprehensible way that doesn't undermine trust or actionability. Despite advice from the World Meteorological Organization (WMO, 2008), the US National Research Council ((NRC, 2008)), and the American Meteorological Society ((Hirschberg *et al.*, 2011)) that weather forecasts should incorporate forecast uncertainty, throughout Europe, media and audiences have traditionally been accustomed to deterministic communications about weather (e.g. tomorrow it will rain or tomorrow it will not rain) (Zabini *et al.*, 2015), and many experts are reluctant to communicate this uncertainty to the general public (Joslyn and LeClerc, 2013).

Despite this, there is argument that people understand that weather forecasts are uncertain even when this information is not made explicit to them, and that they already assign their own degree of uncertainty to these forecasts, which may be less accurate than assessments users might make if provided with a probabilistic forecast upfront (e.g. (Morss *et al.*, 2008; Joslyn and Savelli, 2010; Savelli and Joslyn, 2012))

There has been an increased use of probabilistic communication in weather forecasts, but this can clash with the old deterministic use of icons. There is a concern among some forecasters that if, for example, it rains whilst the prediction was of a low probability chance of rain (and the 'rain' icon was not used), trust could be undermined as the forecast is seen as 'wrong'. Often, then, you see a 'rain' icon being used even when the probability associated with it is low.

As well as conveying uncertainty, probabilistic information is particularly useful in a dynamically changing context as it allows a gradual changing of the probabilities without the sudden switching caused by using categorical, deterministic communication (e.g. chance of rain at a particular time can change from 20% to 40% to 60% as that time approaches, without changing suddenly from ‘no rain’ forecast to ‘rain’ forecast).

When it comes to climate forecasts, specific quantified uncertainties are more commonly communicated. These can be either in projections on graphs (see right), or in some form on geographical representations.



IPCC climate change forecasts under different scenarios, including uncertainty around these forecasts (IPCC, 2014).

5.1.4. Forecast skill scoring

Although not directly related to how they communicate their uncertainties, it’s worth noting that weather and climate forecasters are trained using forecast skill scoring, such as Brier scoring, which is a system designed to punish over-confident wrong forecasts (through calculating the mean square difference between the predicted probability assigned to an outcome and the actual outcome).

As a very simple example (Wikipedia, 2020), suppose that a forecaster is forecasting the probability P that it will rain on a given day. The Brier score is calculated as follows:

- If the forecast is 100% (P = 1) and it rains, then the Brier Score is 0, the best score achievable.
- If the forecast is 100% and it does not rain, then the Brier Score is 1, the worst score achievable.
- If the forecast is 70% (P = 0.70) and it rains, then the Brier Score is $(0.70-1)^2 = 0.09$.
- In contrast, if the forecast is 70% (P = 0.70) and it does not rain, then the Brier Score is $(0.70-0)^2 = 0.49$.
- Similarly, if the forecast is 30% (P = 0.30) and it rains, then the Brier Score is $(0.30-1)^2 = 0.49$.
- If the forecast is 50% (P = 0.50), then the Brier score is $(0.50-1)^2 = (0.50-0)^2 = 0.25$, regardless of whether it rains.

There are a wide range of forecast skill scoring systems. Low probability events present a challenge, but see: https://www.cawcr.gov.au/projects/verification/#Methods_for_rare_events.

The 'skill' level of a climate forecast (i.e. how often that forecast is accurate, over historical time) is often displayed alongside it as a way of communicating uncertainty (Barnston, He and Unger, 2000).

5.1.5. Choosing an appropriate level of detail/precision

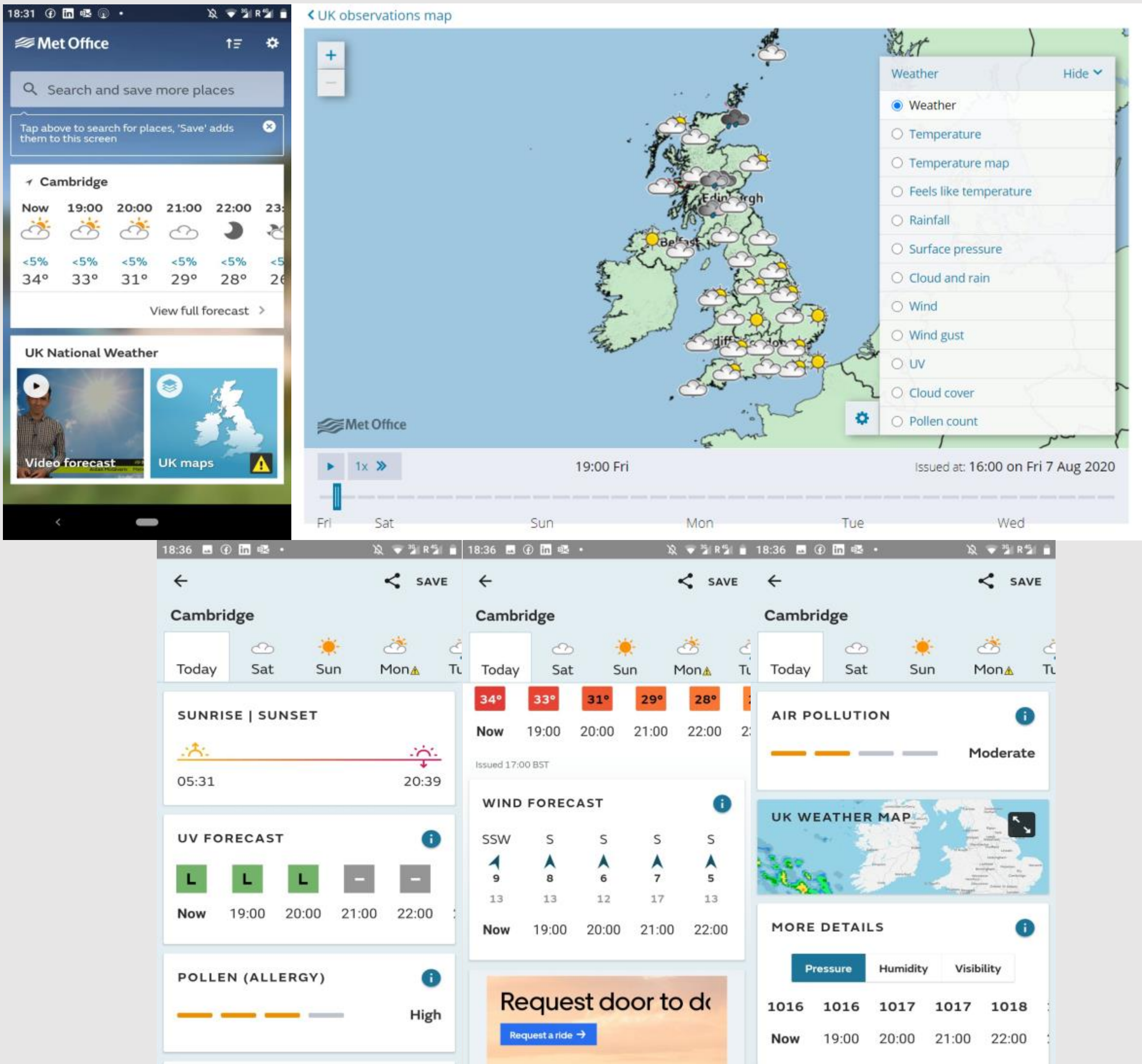
Experts, when interviewed, expressed concern over the level of detail included in weather forecasts, e.g. hourly forecasts. Their worry was that showing such detailed information could lead to false perceptions of accuracy. Indeed, one of the challenges of the forecaster, they felt, was 'to manage the audience's expectations'.

However, with many competing and commercialised outlets for weather forecasts, the 'arms race' means that reducing the amount of information and increasing the communication of such uncertainty is difficult as competitors might not do so and hence could be more popular.

Case study: weather forecast communication in UK Met Office

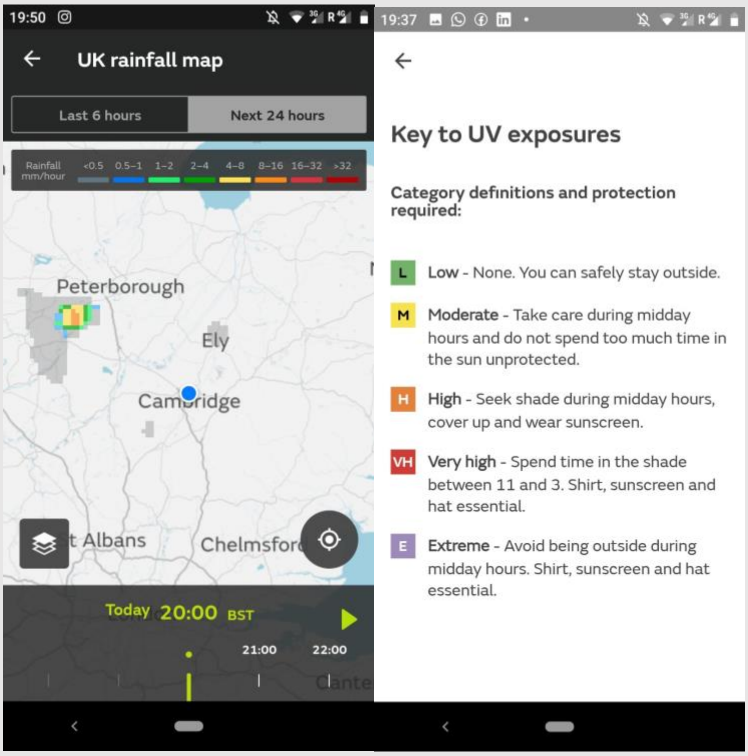
The UK Met Office produce forecasts for use across a wide spectrum of media as well as for audiences ranging from the general public to specialist professionals who want long-range or detailed geographical forecasts.

They use layered communication, with the top-level message being either a daily or hourly forecast (depending on medium and sometimes a default controlled by individual users) including temperature and likelihood of precipitation as the default main messages. They produce both map-based (geography-centric) and location-specific (time-centric) outputs that are designed to be useable by different outlets.



UK Met Office cont'd

Change in space and time
On the UK rainfall map, the rain is displayed showing the last 6 hours as well as the forecast into the next 24 hours. This helps people visualise the movement of the rainstorms and have a deeper understanding of the forecast.



For each type of information, further information is available that can involve behavioural recommendations or threshold measures.

5.2. What is known about the effects on the audience?

5.2.1. The right information?

In 1993, a winter storm hit the Eastern US with such force that hundreds of people died, from exposure, heart attacks as they shovelled snow, road accidents and falling trees. The Weather Channel, a 24-hour weather service had been broadcasting strong warnings and forecasts of the storm in the run up to it hitting the region. Why had so many people died, seemingly caught unawares? The channel called in risk communication expert Baruch

Fischhoff to investigate. In a characteristically insightful piece of work (Fischhoff, 1994), he identified that it was not a problem of the public misunderstanding that bad weather was forecast. What seemed to be a problem was understanding what that weather meant for them. What killed people was the consequences of the storm – the driving conditions, the disruption of the transport system or electricity supply, their attempts to shovel snow. The hazard was communicated, but not the risks associated with it.

Despite the maturity of weather and climate forecasting as a communications exercise, research suggests that a gap still exists between what scientists think is useful information and what users actually find usable for their decision making (Lemos, Kirchhoff and Ramprasad, 2012; Klemm and McPherson, 2017), and society's most vulnerable groups in particular are not benefitting from improvements in forecasting capacity (Allis *et al.*, 2019; Nkiaka *et al.*, 2019). This highlights the need to work with key audiences of weather and climate communications globally, to design communications that are comprehensible and trustworthy for users, and that serve their localised decision making needs. There is considerable evidence that climate services that are co-developed between producers and their audience are those which are most useful (Dilling and Lemos, 2011; Steynor *et al.*, 2016; Vaughan *et al.*, 2016).

5.2.2. Do people understand the information?

Another challenge associated with the rapid development of weather and climate services is that users potentially have access to vast amounts of information that they did not previously (Morss *et al.*, 2017), making it difficult to process and to sort task relevant from task irrelevant information.

Use of icons and symbols has been a popular way of trying to simplify weather forecast information and increase its accessibility by the audience (Keeling, 2010; Zabini *et al.*, 2015). However, a large survey of the public in the Italian region of Tuscany, (Zabini *et al.*, 2015) demonstrated fundamental misinterpretations of common weather icons, as did a study on Norwegians (Sivle *et al.*, 2014), suggesting that such an approach may not be as effective at communicating meteorological information as its prevalence might suggest. (Zabini *et al.*, 2015) note that these misinterpretations might be reduced by providing text-based explanations to accompany the images.

In what seems a sensible hypothesis, (Hegarty, Canham and Fabrikant, 2010) suggested that making the information most relevant to a user's specific tasks the most cognitively salient information in weather maps might help their decision-making. For example, if a weather map shows both temperature (using a colour coded heat map) and pressure information (using isobar lines), but the task the viewer has to do relates to wind speed, then pressure information will be more important to them than the temperature information. A communicator can adapt a weather map to accommodate this by making the pressure information more salient, perhaps by emboldening the isobars and reducing the intensity of the temperature heatmap. Despite the apparent logic of this approach, evaluations of its efficacy have been mixed, with some studies showing visual salience improves task performance provided users have been trained in meteorological principles (e.g. (Hegarty, Canham and Fabrikant, 2010)), and others showing no effect of visual salience, either before or after training (e.g.(Fabrikant, Hespanha and Hegarty, 2010).

5.2.3. Do people understand the uncertainty?

Large studies in the US (over 1000 participants each) showed that over 95% of these participants inferred uncertainty in weather forecasts even when it wasn't being communicated (Morss *et al.*, 2008; Joslyn and Savelli, 2010). They also instinctively realised that shorter lead-time forecasts were likely to be more certain. A significant majority also preferred uncertainty to be communicated and liked a percentage, probabilistic format when given a choice, as well as a concise context for uncertainty if there is one (e.g. the presence of a cold front, whose movement is not easily predicted and can change the temperature forecast from one extreme to another).

It is well-established that the public don't interpret the probabilities the way that forecasters intend, and indeed that forecasters themselves can differ in interpretation (De Elía and Laprise, 2005; Gigerenzer *et al.*, 2005). Much of the issue appears not to be with the probability itself, but with the event that the probability is attached to: does '70% chance' refer to a geographical area over which it will rain, a time period over which it would rain, or the chance of rain occurring or not in a particular location etc? Thus, being clear about the event described may be the key (Fischhoff, 1994; Handmer and Proudley, 2007; Joslyn, Nadav-greenberg and Nichols, 2009; Juanchich and Sirota, 2016)

Despite expert concerns about communicating probabilistic forecasts, there is also now evidence that people make higher quality decisions based on forecasts that communicate numeric uncertainty estimates than they do based on deterministic forecasts or explicit advice. For example (Joslyn *et al.*, 2007) demonstrated that people made more accurate decisions about whether to issue a wind speed advisory when using a forecast that included probabilistic information than when using an equivalent deterministic forecast. Nadav-Greenberg and Joslyn, (2009) found similar results for participants making a decision about protecting roads against icing, as did (Roulston *et al.*, 2006) looking at decision making based on temperature forecasts and (Morss *et al.*, 2008) on precipitation.

This may seem at odds with earlier cited research suggesting that people do not comprehend probabilities, particularly small probabilities, very well (e.g. Kahneman and Tversky, 1979; Stone, Yates and Parker, 1994; Rottenstreich and Hsee, 2001; Hertwig *et al.*, 2004). However as (Joslyn and LeClerc, 2013) note, these studies evaluate people's performance compared to a 'rational' standard, rather than comparing relative performance between forecast communications that do not communicate any uncertainty and those that do. Indeed, in an earlier study (Joslyn and LeClerc, 2012) examined decision quality regarding road salting based on probabilistic compared to deterministic forecasts across a variety of different forecasted probabilities of freezing temperatures. The rational choice was to salt the road whenever the probability of freezing was at or above 17%, and the study showed that decisions using the probabilistic forecast were significantly closer in value to what the outcome would be under purely rational conditions. In further encouraging results from this study, participants' levels of trust in the probabilistic forecast were higher than they were in the deterministic forecast.

It should be noted however, that in a condition where the forecast of freezing was just above the normative threshold of 17%, decision making using the probabilistic forecast was poorest in quality; people chose to salt the roads only 35% of the time. The provision of decision making advice improved the quality of decision making up to a value of 49%, however the authors argue that for high impact, low probability events, where action may need to be taken even where the absolute probability of the event is low (such as hurricanes, earthquakes or tornadoes) probabilistic forecasting using absolute probabilities may not be as helpful for decision makers as compared to deterministic forecasts.

In a complementary study, (Le Clerc and Joslyn, 2012) tested whether using an odds ratio format for expressing uncertainty - which makes explicit the relative change in risk compared to a particular baseline - improved decision making compared to the uncertainty format using absolute risks. They found that likelihood of salting at low probabilities of freezing increased substantially to between 70 and 90%, although they showed that the likelihood of salting also increased below the 17% normative threshold. This suggests that while relative risk communications seem to encourage more cautious decision making (as might be useful for the low probability, high impact events mentioned above), they do not lead to normatively better decisions. Clearly then, the choice of format in which the probability is expressed has measurable consequences for decision making and this should be borne in mind when choosing if and how to communicate uncertainty.

Of course, a probabilistic forecast of very low frequency events is also very difficult to verify (since the events happen so rarely) and public reactions to them may well be very different.

5.2.4. Verbal versus numerical communication

The literature around communicating risks and uncertainty verbally rather than numerically is large, and includes many studies in weather and climate. The universal conclusion is that verbal scales are interpreted differently, both within expert groups and public audiences and so verbal terms cannot be relied upon to communicate quantitative measures or degrees of uncertainty (e.g. (Patt and Dessai, 2005; Budescu, Broomell and Por, 2009; Budescu, Por and Broomell, 2012; Harris *et al.*, 2013; Budescu *et al.*, 2014; Morss *et al.*, 2016).

6. Best practice in communicating storm and hurricane risks

A storm, tornado or hurricane forecast has many similarities to an earthquake forecast: it is a potentially catastrophic event that occurs in certain geographic regions with higher frequency than others, and whose forecasts are subject to a number of uncertainties in both time and space. They do, however, have the distinct advantage of being visible to satellites!

6.1. What is being done in practice

Hurricane related deaths in the US have been reduced by 90% compared to 1950s expectations (Rappaport, 2000). The dominant contributor to this are timely evacuations in response to hurricane forecasts (Rappaport, 2000; Gladwin *et al.*, 2009). Data visualisations are an important source of information during uncertain hazard events such as hurricanes (Padilla et al. 2020). Evidence from the US shows that during storm events, the public depend on news broadcasts to inform decisions about evacuation (e.g. Driscoll & Salwen, 1996; Lindell et al. 2005; Lindell & Perry, 2004), which typically use visualisations of hurricanes to communicate storm risk (Padilla at al. 2020). Clearly, ensuring timely communications about hurricanes and other storm events that are comprehensible, trustworthy and actionable will be vital to the continued efforts to reduce losses from these events.

Forecasts usually use one of two formats: a satellite image showing the current location and extent of the storm with graphical representations of its forecast route, or a purely graphical forecast of its trajectory.

6.1.1. Communicating small probabilities

Storms (especially tornados) can be very localised and very transient in time, which means that the probabilities of them occurring in any one place is very small. Forecasters discovered that if they were forecasting over too small a spatial area or time period, then the probabilities for even 'high likelihood' events (in their mind) seemed very small to their audience. But if they increased the time/space over which they were forecasting to increase the probabilities to those which people might take notice of, that made it difficult to increase the probability meaningfully during the day as certainty increased. This has required careful tailoring, finding the right balance for the audience in terms of the size of area being forecast for and the type of messaging being used (see NOAA case study).

6.1.2. Communicating uncertainty

The biggest challenge in communicating a storm warning is dealing with the multiple uncertainties in the forecast: the timings of the storm's projected movements; the force of it at each time point; and the trajectory of the eye of the storm.

Storm forecasts in the US generally use text and quite sophisticated terminology because their expert users will understand it. It's more difficult for them to communicate to a public audience and most of the work that has been done on public communications relate to hurricane forecasts. User understanding of forecast uncertainty is a vital component of informed decision making regarding hurricane evacuation choices.

Ensemble data is the most common type of forecast data used in weather and climate forecasting (Sanyal et al. 2010), and one that makes the geospatial uncertainty in a forecast explicit. Once multiple data values or "ensemble members" are produced (e.g. from runs of individual forecasting models), they are visualised by plotting each on the same Cartesian coordinate plane such that all values can be viewed in an "ensemble display" and so making the geospatial uncertainty in such forecasts clear (Brodlie, Osorio & Lopes, 2012; Potter et al. 2009; Harris 2000; Padilla et al. 2017).

Despite use of such displays within the scientific community, when communicating to the public ensemble data are often simplified into summary displays that detail summary statistics based on the underlying ensemble data (Pang, 2008; Whitaker, Mirzargar & Kirby 2013).

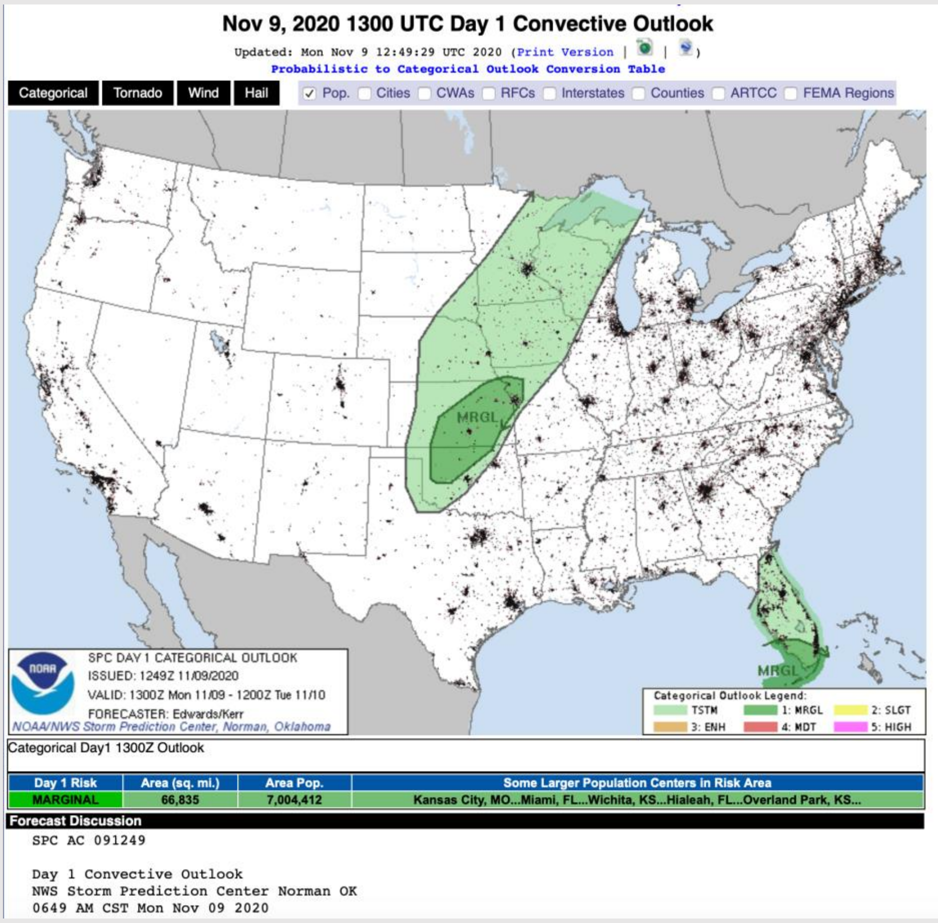
6.1.3. Giving emergency advice in a dynamically changing situation

Once a storm like a tornado is actually occurring, forecasters can give warnings about duration for the location, to within 15 minutes. What is vital is that the audience already know how to respond to the warnings, and when they might 'expire'. Training is done in schools in the US in areas where tornados or hurricanes are likely, and this is effective. In one district, when a storm struck, no one between the ages of 5-22 were killed, and only one parent of a child who had been in school during that time. This probably demonstrates the long-lasting effect of training.

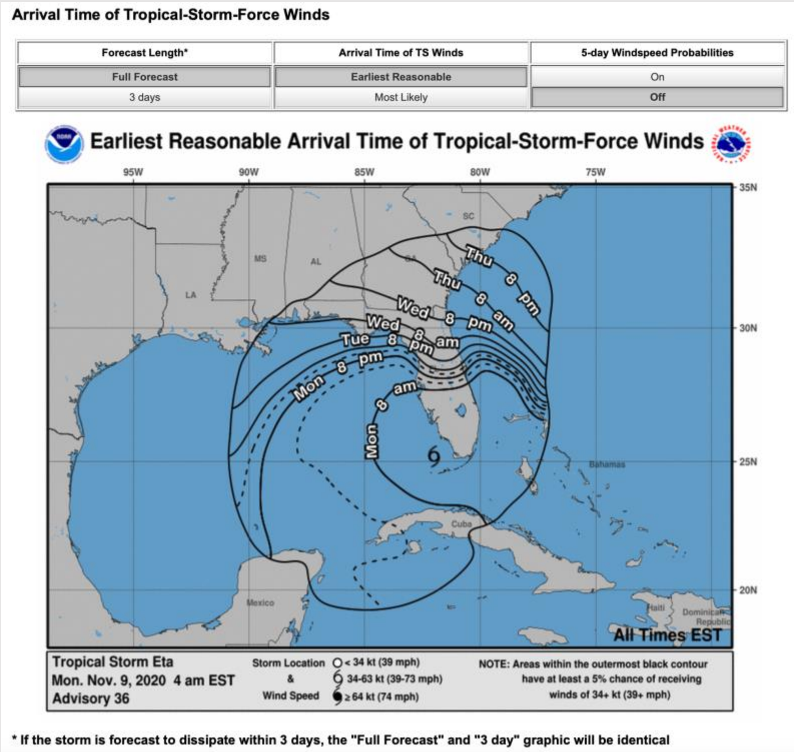
Case study: US National Oceanic and Atmospheric Administration’s storm warnings

NOAA’s earliest storm forecast warnings date from the 1950s, and a lot of the methods used to communicate them have changed little since the 1970s, when their main targets were expert user groups such as emergency management and local meteorological centres. Since the 1990s they have been using probabilistic and numerical communication rather than just verbal terms of likelihoods.

Because of this legacy, and the fact that it’s difficult to change existing systems, their communications are not optimised for a public audience. However, they are well-attuned to their expert audience.



NOAA cont'd



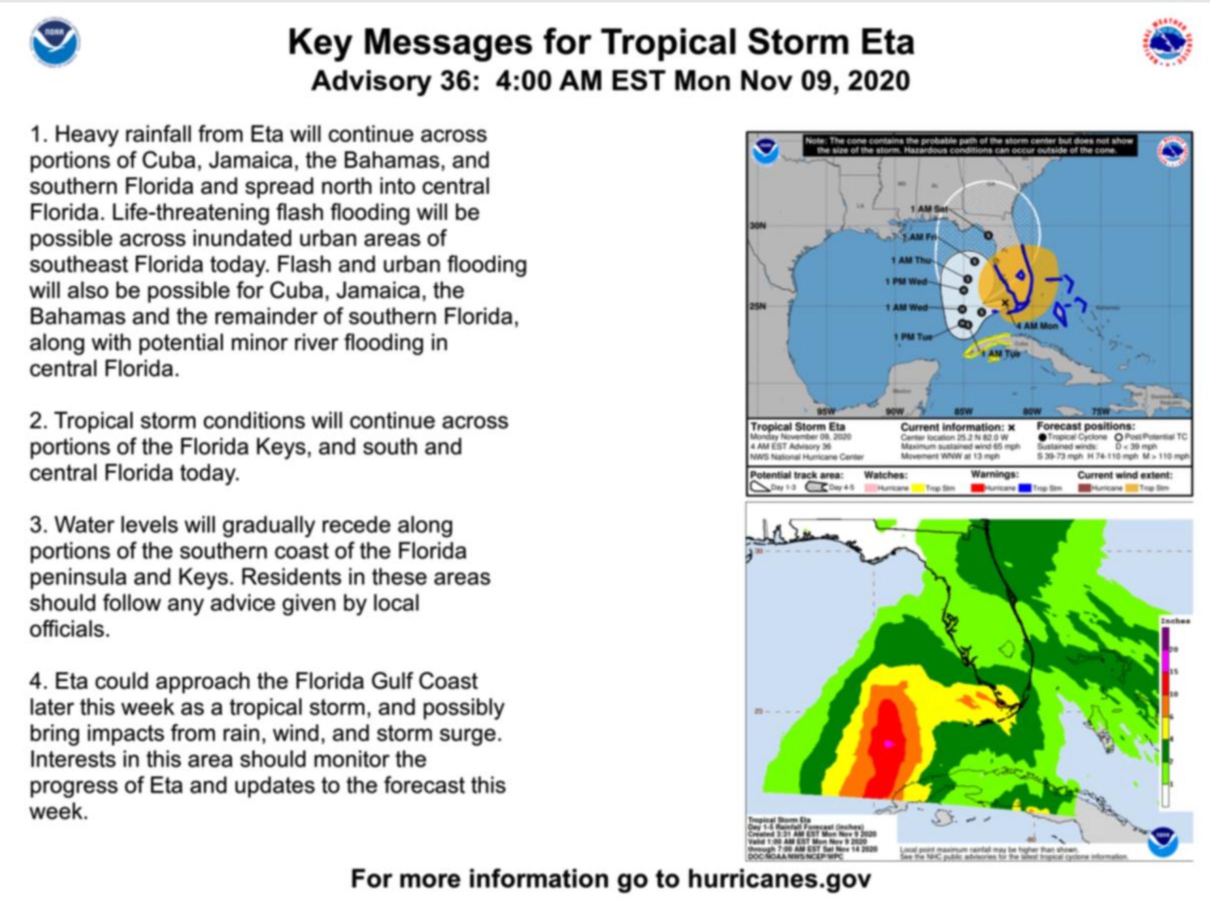
The communication of changes over time – such as the arrival time of a storm – is still relatively complex to try to get across in a still image (see above), and uncertainties are also a key focus. The way that uncertainties in time and space (such as the likely track of a hurricane) are communicated to a public audience is something that is being researched (see following section).

NOAA cont'd

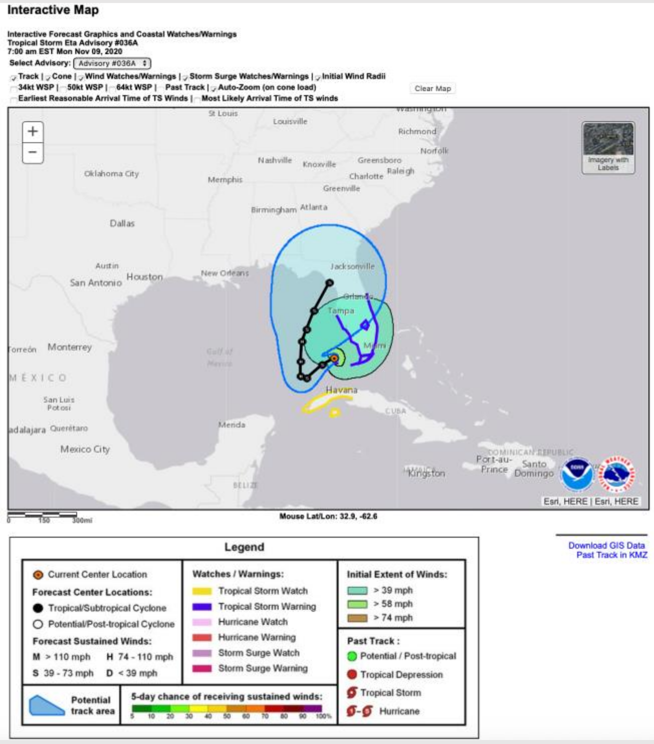
The forecasts involve text warnings and there is an interactive map on the website which allows the audience to select what storm outcome they are interested in, and over what kind of background (showing cities, major road networks etc).

Graphics had evolved with print, where they couldn't show continuous gradients, however now that this is possible, graphics are moving towards that, and away from categorical colour bands. If colour bands are used, what's important is to ensure that they are comparable across different products. For example, one problem at the moment is that wind speeds can be represented by two very different scales (tropical storm force or hurricane force), but each share the same colour scale. This difference was used in 'Sharpiegate' - when President Trump mistakenly listed a hurricane as having the potential to affect Alabama, and a map of the cone of uncertainty was changed to represent his assertion. NOAA issued a statement saying that 'tropical storm force winds' could affect Alabama. The colours used on tropical storm and hurricane forecasts were the same, although the wind forces represented were very different, and it is possible that someone mistook the forecast of tropical storm force winds for one of hurricane force winds.

For hurricanes and tropical storms, NOAA produce a 'key messages' document to accompany the more technical bulletins, which help translate the details for a public audience.



NOAA cont'd



Given that severe storms like tornadoes tend to be very localised and very transient there is a big trade-off in terms of false alarm rate: it is impossible to pin-point the exact path of the storm, and yet it has high impact. Only research can help: into the public's tolerance for false-alarms and missed forecasts, plus careful communication about uncertainty and rapidly changing alerts (e.g. 'This alert lasts 30 minutes. Seek cover now. If you do not experience a tornado within the next 30 minutes then it has passed your location or dissipated and it is safe to leave shelter').

The importance of terminology is also important: people's different interpretations of verbal terms (such as 'moderate'), but also the fact that some categories of risk might be trigger-thresholds for certain emergency procedures. They discovered how important it was that they, as forecasters, knew the difference to the emergency services of moving from one category of risk to another: it might trigger the closing of schools in certain localities etc.

The communications chain with broadcasters can be very two-way in the US. Local information is important, so the Storm Prediction Center have an official chat room where local broadcasters and people with a log-in can give a local weather check ('how big are the hailstones where you are?') which can feed in to the forecast. The broadcasters therefore know the background: what storms are brewing but not yet triggering a warning etc. The forecasters also have a contact list of emergency managers, schools, infrastructure managers and broadcasters that they ensure that they contact if there is a warning to be made. Twice a year they have a media workshop training people on how to interpret the information and report it – but it's all about trust and relationships (and two-way communications).

Case study: UK Met Office's weather warnings

The UK's Met Office creates severe weather alerts, which are sent out through several channels including their own app, SMS notifications to subscribed users and partnerships with media channels, as well as a tailored communication specifically for decision-makers such as local emergency responders.

There are two aims to the warnings:

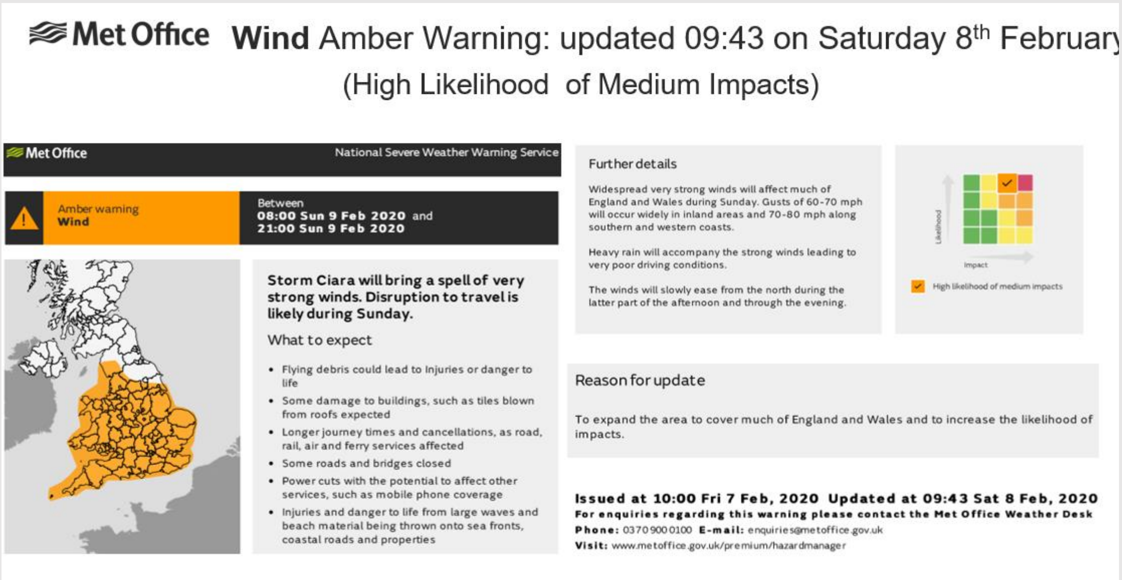
- alerting people of severe weather to help them get prepared for it
- helping people make decisions about what actions need to be taken

In order to do this, the messages tend to comprise:

- **What** the hazard is (e.g. rain, wind, snow, fog)
- **Where** (location shown on map)
- **When** (time frame, with the sentence "between … to….")
- What to expect as a **result**
- **Further information link** (e.g. how much snow is expected)

Depending on the audiences and situations, it may also contain:

- Level of risk and severity through a risk matrix
- What's happening at the moment
- Expected impact
- What to do



The warning is by default sent to people who are located in the warning area where there is a higher than 50% probability of a 'medium' impact affecting a 'wide range of people'. The information is usually issued 2-3 days in advance (minimum 2hrs in advance of an event, but for a larger event, the more notice the better) and then updated daily for emergency responders, with more sporadic public updates. Giving a warning too long before an event is perceived as potentially leading to a devaluing of the accuracy and trustworthiness of the information.

Their alert messages are carefully worded, stressing the fact that only a few areas will be affected to avoid creating false alarms over a wide area: e.g. *"Most places will not be affected, however isolated thunderstorms will bring severe trouble disruption in some locations."*

They frame their public messages as a story as well as embracing a layered communication approach, with a simple overview of the message linking down to deeper information. One challenge is that after a public warning, there is increased public traffic to helplines asking for personal confirmation of the warning.

For emergency responders, they provide a risk matrix (see image above) although note that they have reports of the colour banding being confusing as it doesn't always match behavioural advice) and verbal communication of probabilistic information ("is likely to", "is possible to", "is probable to", "will") alongside it. The Met Office use verbal terms instead of numeric probabilities in their weather warnings, although they use a specific set of language translating probabilities into these verbal terms:

Matrix Likelihood Label	Best Practice Likelihood %	Word/Phrase
High	>80%	Definitely, Certain, Will happen, Almost Certain, Very Likely, Expected
Medium	50-80%	Anticipated, Good Chance, Likely, Probably (Probable)
Low	30-50%	Possible, Might, Potential, Maybe, Perhaps, Could Happen, Chance
Very Low	10-30%	Slight/Small Chance, Not Likely, Unlikely
Very Low	<10%	Not expected (therefore no warning issued)

Matrix Impact Label	Recommended Word/Phrase
High	Dangerous, Very Serious
Medium	Large, Substantial, Some
Low	Minor, Few
Very Low	Limited, Negligible

Met Office Term	Recommended Word/Phrase
Isolated	Few places/here and there
Localised	Some places/small area
Widespread	Extensive
Widespread	Over a large area

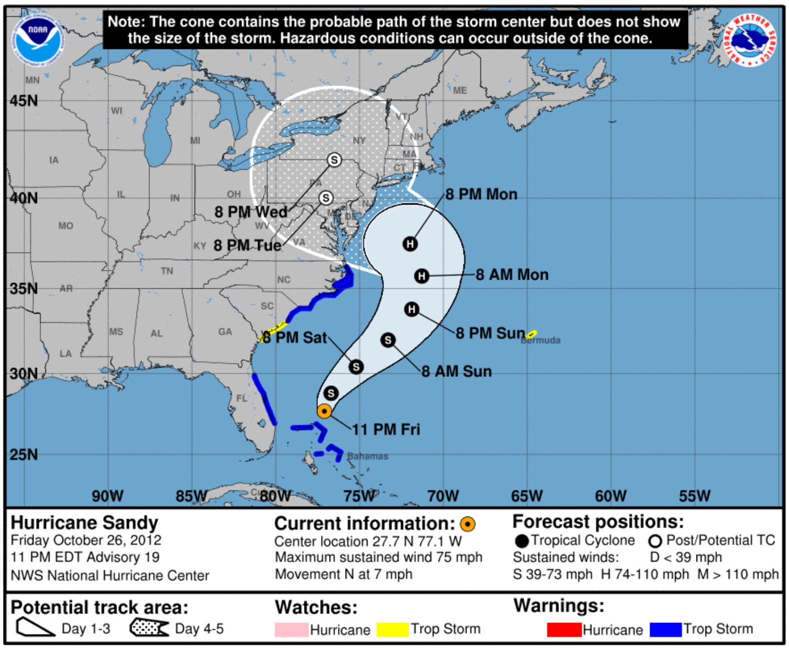
Word(s) not to use	Rationale	Suggested alternative
Localised/isolated	It is meaningless to those outside meteorology	Some places, small areas
Confidence/confident	Feedback suggests that confidence implies an individual's personal view and the message is not considered authoritative or reliable	Use likelihood words to convey the level of certainty. Describe issues leading to uncertainty in the Further Details section, if appropriate to do so
Best estimate	Interpreted as guessing	Use likelihood words to convey certainty
Uncertainty	Uncertainty is overused	Every warning is inherently uncertain, therefore it is not necessary to state it all the time. Using the likelihood words will convey probability without stating 'this forecast is uncertain'. Phrases such as 'it is possible that the impacts could occur further north' conveys uncertainty without stating 'it is uncertain'.

6.2. What is known about the effects on the audience?

Extreme weather event forecasting has received specific attention in the literature, with the US hurricane forecasting system being thoroughly analysed from forecaster to end users by (Bostrom *et al.*, 2016). They interviewed 8 National Weather Service forecasters, 5 broadcasters, and 6 public officials in Florida to map their decision-making and communications pathways. It highlighted that although communication was good between the forecasters and the broadcasters and public officials, there was a proliferation of products which could be streamlined and better adapted to the users' needs. A clear concern of all was the communication of uncertainty, and the need to communicate impacts rather than just hazards. (Potter *et al.*, 2018) show that communications that integrate impact information into the communication affect people's perception of the risk and understanding of potential impacts more than warnings based only on hazard information, although they show that this does not have an influence on how much action people undertake in response to the warning. They also highlight the need to include information on what people should do in response to the warning.

In another evaluation of the US National Weather Service's communication of hazardous weather information, (Demuth *et al.*, 2013) highlight the need to improve communication of threat existence, but also of the dynamic nature of weather hazards and their varied periods of potential impact, by providing information on threat timing. They demonstrated that providing coupled text detailing start and end time of both a short-duration severe thunderstorm warning and a longer duration flood-watch improved participants' understanding of the precise timing the warnings were in effect.

6.2.1. Do people understand summaries of ensemble models?

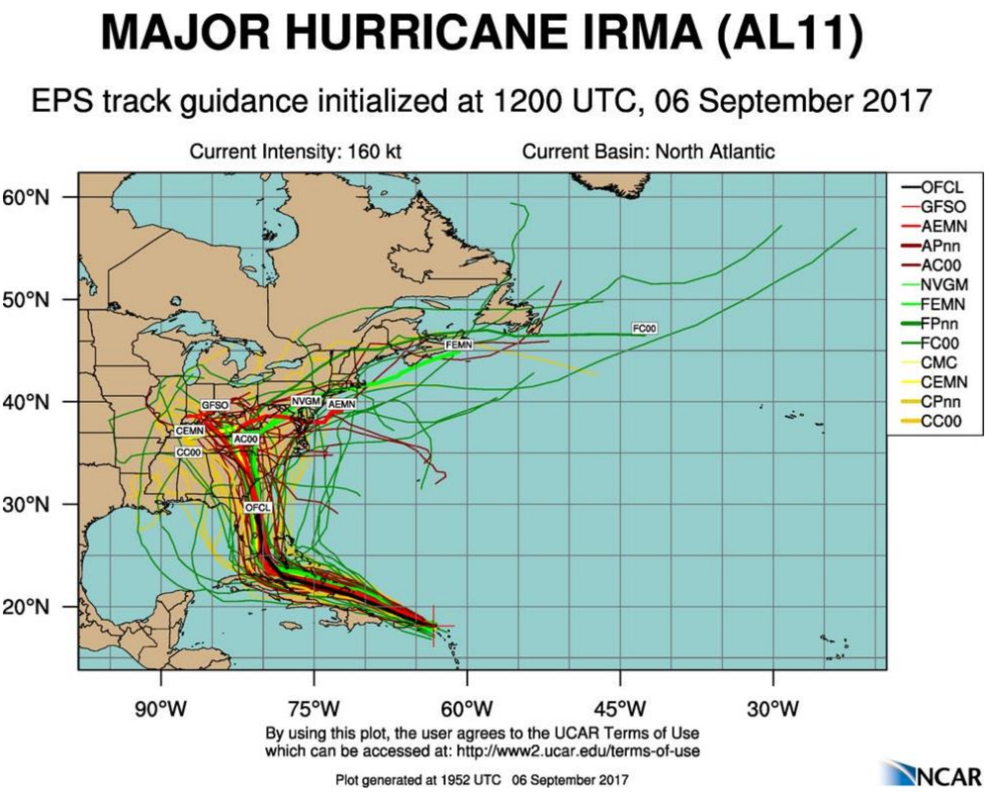


Example forecast for Hurricane Sandy, Friday 26th October 2012 from the National Hurricane Centre, USA. They use a summary display to depict the average forecasted path of the hurricane and the uncertainty associated with that forecast.

Whilst hurricane forecasters typically use ensemble modelling, they then convert their ensemble results into a summary graphic for their audiences. It is argued that summary displays are easier for the viewer to understand than a full ensemble model (Padilla et al. 2017). For example, chloropleth maps (that use colour to encode summary statistics rather than plotting all individual data points) may be easier to comprehend than ensemble displays (Harrower & Brewer 2003; Watson, 2013), and may decrease mental workload and thus reduce task performance time (Dobson 1973; 1980).

Recent work, though, has suggested that there are some negatives to these kind of summary displays (Padilla et al., 2017). Besides hiding important characteristics of a dataset such as bimodality or skew (Whitaker, Mirzargar & Kirby, 2013), there is evidence that summary displays can lead to biases in decision making as compared to ensemble displays (Correll & Heer, 2017) and can be misinterpreted by both public and expert audiences (Belia et al. 2005; Newman & Scholl 2012; Savelli & Joslyn, 2013).

The value of summary versus ensemble displays has been evaluated rigorously for hurricane forecasts. Such forecasts are typically communicated in a particular format of summary display – a hurricane cone, or cone of uncertainty – that provides information on the forecasted track of a hurricane through space and time and the uncertainty associated with that summary forecast in the form of a 66% confidence interval and calculated by averaging historical hurricane forecast tracks over a five year period (Cox et al. 2013; Padilla et al. 2017) (e.g. the figure above). Alternative, ensemble displays have been developed to communicate the same information, but illustrating each individual path the hurricane could take, rather than the summary statistics that the cone display uses (see below).



There is increasing evidence to suggest that ‘cone of uncertainty’ summary displays can be interpreted in a biased way by the viewer. For example viewers have been shown to assume that locations in the centre of the cone that are at a later point in time will receive more damage than those at an earlier point in time, although this bias also exists for ensemble representations but in the opposite direction (Ruginski et al. 2016). Furthermore, viewers have been shown to be significantly more likely to report that the display shows the size of the hurricane growing through time when viewing a summary cone style display than when viewing an ensemble version, rather than the correct interpretation which is that what is represented is the increasing uncertainty of the forecast over time (Ruginski et al. 2016; Padilla et al. 2017). Padilla et al. 2017 further demonstrate that the salient visual features of both the cone (its increasing size) and the ensemble display (its diverging tracks) can bias participant judgements about the hurricane being forecasted. They demonstrate that although ensemble displays may better communicate the concept of uncertainty in the forecast, when used to make point-based judgements about impacts at specific locations, individual ensemble members may be overweighted in their decision making. They thus go onto suggest that decisions about which visualisation to use should be informed by the task the viewer is expected to perform using the visualisation (Padilla et al. 2017). (Padilla, Creem-Regehr and Thompson, 2020) go on to demonstrate that this bias can be reduced by changing the number of hurricane tracks the display depicts, and providing a text explanation of the display, although in neither case is the bias fully eliminated.

6.2.2. Evaluations of tornado alerts

Evaluation of communications about tornados have also received some attention in the literature. Many studies focus on the alert system and associated terminology used by the US National Weather Service who communicate categories of alert in their tornado communications (and their communications about many other hazards, such as flash floods). Specifically, they issue alerts in two categories. The first is a “watch” which indicates an increase in the risk of an event in a particular area. The second is a warning, which indicates that an event is highly probable, imminent or occurring in that area (Morss et al., 2016). This gradation allows meaningful updating of information in real time as the forecast of the event changes.

Results of tests of comprehension of these two types of alert have been somewhat inconsistent (Ripberger et al., 2019). Whilst some studies demonstrate that the vast majority of people can understand the distinction between a tornado watch and a tornado warning (Balluz *et al.*, 2000; Schultz *et al.*, 2010), others show comprehension is much lower (Powell and O’Hair, 2008; Mason and Senkbeil, 2015). (Ripberger *et al.*, 2019) suggest that much of this variation likely comes from geography and sampling methods, although there is also some demographic variation, with comprehension increasing with age (Powell and O’Hair, 2008; Sherman-Morris, 2010), and variation due to geographic variability in amount of exposure to these types of alerts (Powell and O’Hair, 2008). Having identified many measurement inconsistencies between these various studies of audience reception, comprehension and response to tornado warnings, (Ripberger *et al.*, 2019) have attempted to develop a robust, reliable survey measure of these concepts that is still sensitive to demographic and geographic variation in response. Their data and code are open source and can be found here: https://github.com/oucrcm

6.2.3. Do people take action as the result of a warning?

Of course, as discussed earlier, in some cases the desired outcome of a communication is not just to inform, but to encourage action of some sort, from basic preparedness through to more extreme responses such as evacuation. Thus many studies have also examined people's behavioural responses to these National Weather Service Alerts. Studies that measure behavioural response are quite varied in their findings about the proportion of people responding to tornado warnings (e.g. (Balluz *et al.*, 2000; Chaney *et al.*, 2013; Miran, Ling and Rothfusz, 2018), whilst those that report on behavioural intentions are more consistent, finding that between 75% and 90% of participants intend to take action upon receipt of the next tornado warning they receive (e.g. (Schultz *et al.*, 2010; Ripberger, Silva, Jenkins-Smith and James, 2015; Ripberger, Silva, Jenkins-Smith, Carlson, *et al.*, 2015; Lindell *et al.*, 2016; Ripberger *et al.*, 2019)). This difference in consistency perhaps speaks in part to the gap between behavioural intentions and actual practiced behaviour, and should be borne in mind when considering the results of these sorts of studies.

There is again variation in response to these sorts of communications according to different demographics (Ripberger *et al.*, 2019). For example responsiveness seems to increase with education level (e.g. (Balluz *et al.*, 2000)) and initially with age, although after a certain point the age relationship is inverted (e.g. (Senkbeil, Rockman and Mason, 2012; Chaney *et al.*, 2013)). Additionally, men are typically less responsive than women (e.g. (Sherman-Morris, 2010; Ripberger, Silva, Jenkins-Smith and James, 2015; Robinson, Pudlo and Wehde, 2019). Clearly then, even within a public audience, different types of people respond in different ways to such warning communications.

6.2.4. Is there a worry about 'false alarms'?

Successfully providing people with advanced warning of a hazard can save lives, for example (Simmons and Sutter, 2008) demonstrated that tornado warnings with lead times up to 17 minutes reduce injuries and fatalities from these events. There is an inevitable trade-off, however, between probability of detection of a hazard event and the number of false alarms. If you never issue any warnings, you never issue false alarms but of course you also never successfully warn people about actual events that do occur. If you issue a warning for every forecasted event then your event detection success rate is 100%, but at the cost of potentially issuing a multitude of false alarms (Simmons and Sutter, 2009). How this trade off should be satisfied depends on what the effects of false alarms are, for example do they reduce people's engagement in preparedness actions or willingness to continue using alert delivery devices, and do they increase the incidence of casualties from hazard events?

Thus far, evidence for the effects of false alarms have been mixed. Some studies have shown that false alarms do not affect confidence in warning systems (e.g. (Schultz *et al.*, 2010)), whilst others show little negative impact of false alarms on decision making in response to warnings (e.g. (Dow and Cutter, 1998)). However, other work on tornado early warning systems has demonstrated that the false alarm rate is strongly related to tornado fatalities and injuries, possibly by reducing responsiveness to warnings (Simmons and Sutter, 2009), perhaps because they undermine credibility of the organisation that issues the alert in the first place (Ripberger, Silva, Jenkins-Smith, Carlson, *et al.*, 2015).

Although in the immediate aftermath of a false alarm the precise details of what went wrong or the true nature of the hazard in question might not be known, research suggests that rapid communication in times of crisis may help maintain trust in the communicating organisation (e.g. (Covello, 2003; McBride *et al.*, 2020)). Thus a dynamic system of post-alert updating, where the audience are rapidly advised of any mismatch between the alarm and the actuality of the event, and potentially given an "all-clear" message, may be one solution to any problems associated with false alarms (McBride *et al.*, 2020).

6.2.5. The challenge of misinformation

False rumours are a problem around hurricanes and other storms, just as they are around all sorts of events. For example, in 2017, as both Hurricanes Harvey and Irma approached the US coast, rumours spread on social media that evacuation shelters were checking people's immigration status. Of course this could discourage many residents from seeking safe shelter. (Hunt, Wang and Zhuang, 2020) followed the spread of the rumour and its corrections on Twitter. Official corrections from government offices were the most retweeted, followed by messages from other verified accounts and news agencies. The rumour also had far less traction the 'second time around' when Hurricane Irma hit, after considerable correction activity after Hurricane Harvey. This shows the importance of credible sources and the power of both government and major media sources in debunking rumours on social media.

6.2.6. Words or numbers?

Weather warning systems such as those discussed above provide some uncertainty information through categorical warnings based on likelihood of occurrence, or categories that combine likelihood and severity (e.g. the US National Weather Service's watch vs warning system; the UK Met Office's Yellow, Amber and Red alert system). However as discussed earlier, there are very large variations in the numerical values people attach to such verbally described probabilities, as evaluated extensively in the weather and climate change literature. Underestimations of the risk that should be attached to each category may be one explanation for sometimes observed low compliance rates with emergency protocols such as evacuation (Joslyn and LeClerc, 2013). Attaching numeric probabilities to verbal category terms can improve people's accuracy in assessing the terms however (e.g. (Budescu *et al.*, 2014)). And indeed, the studies discussed above that show improved decision making when uncertainty information is communicated all use numeric formats in their communications.

7. Best practice in communicating flood risks

Flooding, particularly flash flooding, can be a catastrophic risk. Rather like seismic risk it has both geographic spread and temporal components as well as a magnitude of impact, all of which can be uncertain.

However, it also has long-term components, with residents of areas at risk of flooding being made aware of the possibility of flood, how to prepare for it, what alerts and warnings are available, and the flood risk also has implications on planning and construction.

7.1. What is being done in practice

7.1.1. Being prepared

Flood risks are well prepared-for in many countries. For example, many have emergency protocols triggered by automatic level detection in water gauges. This can give a lead-time of several days for local decision-makers and emergency responders to put plans into action. Having an emergency protocol in place means that messages can be shorter and clearer: people already know what to do, they just need telling that an emergency protocol has now been triggered. For example, in Zambia there is a flood warning system using WhatsApp to alert the Red Cross and government figures, and an email system that goes to local leaders.

What has proved important in all countries is training with the relevant stakeholders to ensure that they know the protocols and understand the communications. Involving them in the design of the communications system ensures that they have 'buy in' and that it suits their needs, as well as ensuring that appropriate and well-understood language/graphics are used.

7.1.2. Communicating the potential impact

There are many types of flooding (e.g. coastal, river, surface water) which each pose a different kind of impact. Both the potential depth and the potential velocity of moving water pose thresholds for flood warnings.

Another problem is that impacts vary hugely over short geographical distances: houses slightly further from a river, or on slightly higher ground, may not receive any damage at all compared to their surroundings.

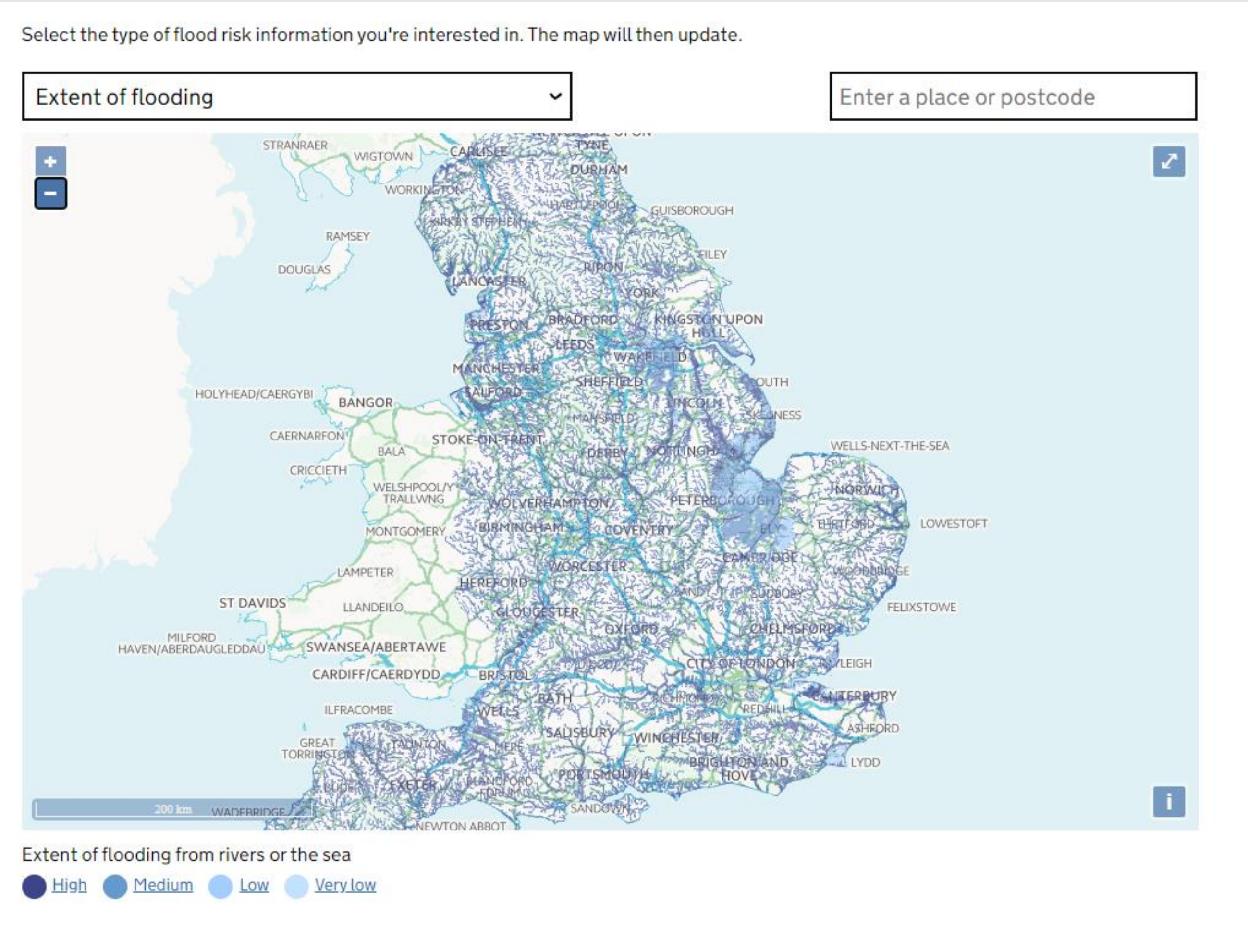
Case study: UK Environment Agency and Met Office

The UK's flood communication is designed to increase awareness of the hazard, help people understand risk, prepare for floods and be prepared to deal with the aftermath of them. 'Flood resilience' is what they aim to help provide, and they do a lot of local community work to ensure that local people buy in to the solutions being provided.

Preparation
'Resilience engagement advisors' work locally with schools, businesses and local communities to help them prepare for floods.

General risk
Non real-time modelling provides a hazard map showing the level of risk to each geographic location over a 1 year period. The map is searchable and zoomable and gives a colour coding for four levels of risk: High (dark blue), Medium (mid blue), Low (light blue), Very low (very light blue). These correspond to annual likelihoods of flooding of >3.3%, 1-3.3%, 0.1-1%, <0.1%.

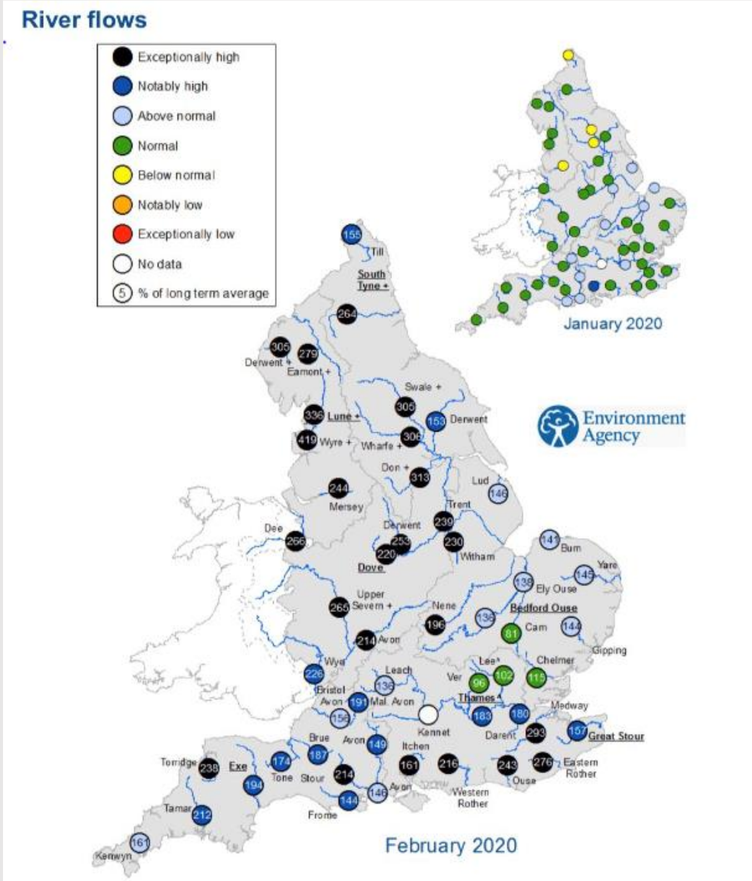
'Traffic light' colour coding is not used because this is not an emergency situation.



UK Environment Agency & Met Office cont'd

Communicating medium-term trends

Flood risk can increase over the medium-term, as detected by changing water levels. This increasing risk over both time and space can be communicated by colour-coded percentage increases in water levels at different geographic locations.



^ "Naturalised" flows are provided for the River Thames at Kingston and the River Lee at Feildes Weir
\+ Monthly mean flow is the highest on record for the current month (note that record length varies between sites)
Underlined sites are regional index sites and are shown on the hydrographs in Figure 3.2

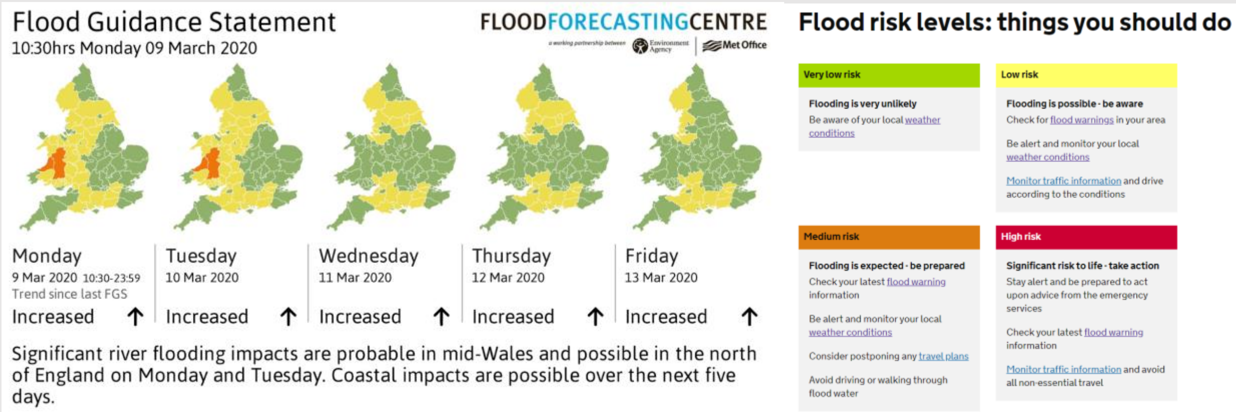
Figure 3.1: Monthly mean river flow for indicator sites for January and February 2020, expressed as a percentage of the respective long term average and classed relative to an analysis of historic January and February monthly means (Source: Environment Agency). Crown copyright. All rights reserved. Environment Agency, 100024198, 2020.

UK Environment Agency & Met Office cont'd

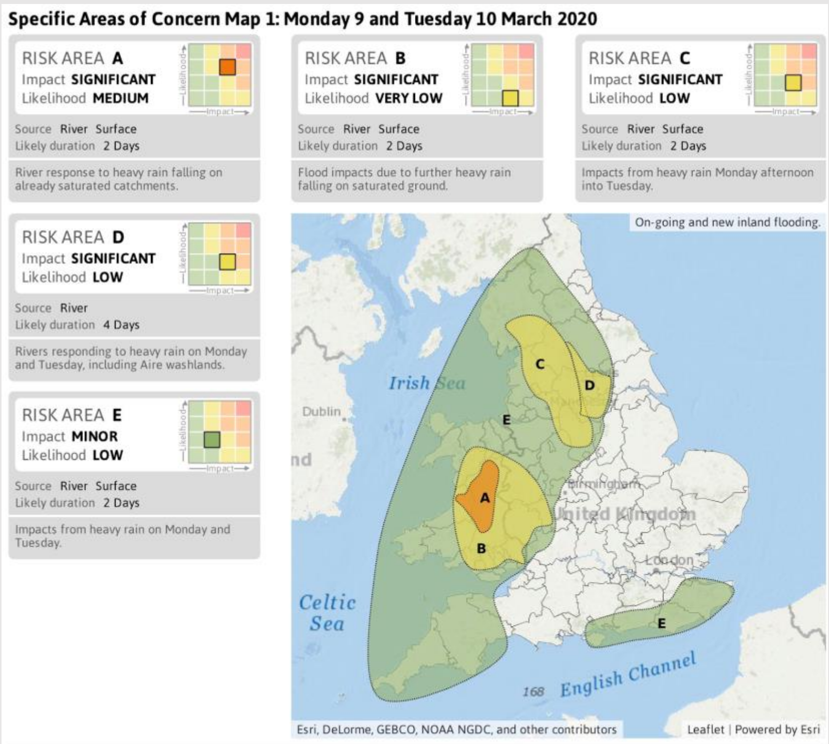
Short-range forecasting

The likelihood of flood is forecast daily for the next 5 days via a series of 5 maps on the Environment Agency website. This is done every day to ensure that everyone is used to the system and when a flood comes, people are not 'on the back foot' and are pro-active, not reactive.

Four colours are used to communicate four levels of risk: Very low (green), Low (yellow), Medium (orange) and High (red). Alongside the map is text which is designed to be action-focussed and easy to understand, and an arrow showing whether the risk is increased since the last statement or decreased. The broad scale of the map is designed to help emergency planners rather than the public. These stakeholders are also e-mailed a flood risk matrix showing likelihood and impact. Beyond 5 days the uncertainties in the forecast become too high to be useful. Numerical probabilities are only shared with governmental partners – all others get verbal statements as feedback suggested they wanted a 'simplified' approach. A telephone contact number is provided to answer further questions.



Public short-term flood warning



UK Environment Agency & Met Office cont'd

Flood warning

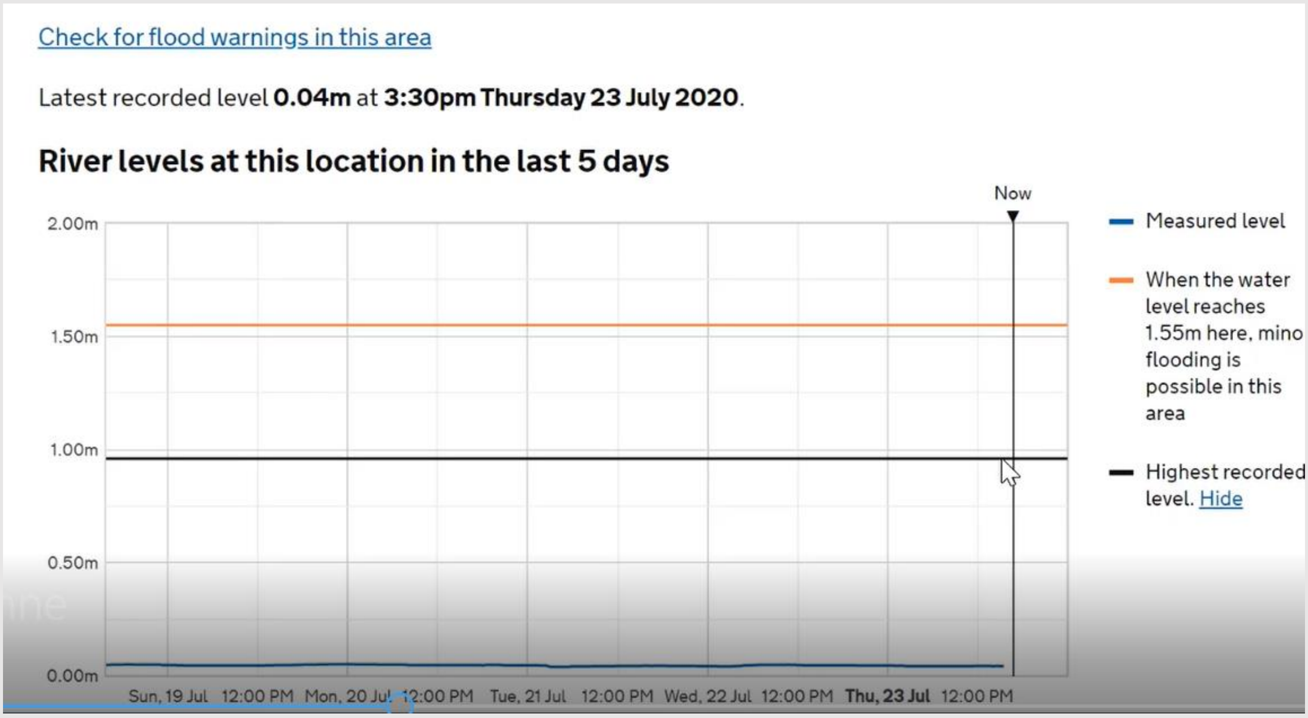
Flood warnings and short-term flood forecasts are based on real time modelling where information is continuously updated according to the rainfall forecast and observations. 6-12 hours in advance of a forecast flood, when a certain threshold is reached, an automated public warning system is triggered, which sends an alert to all phones in the areas at risk (no subscription necessary). This system has been in place since 1996. The time frame is chosen to allow people enough time to prepare but to be close enough to the forecast event to minimise uncertainties, and increase people's confidence in the forecast as well as minimise any period of distress as they prepare.

The media, social media, emails and stakeholders such as local authorities, volunteer organizations and the emergency services are all used to issue the warnings.

For public communications, they try to relate the forecast event to a recent historical one to help give context to the expected impacts (e.g. 'the last time it flooded to this extent was 2007').

Localised public information

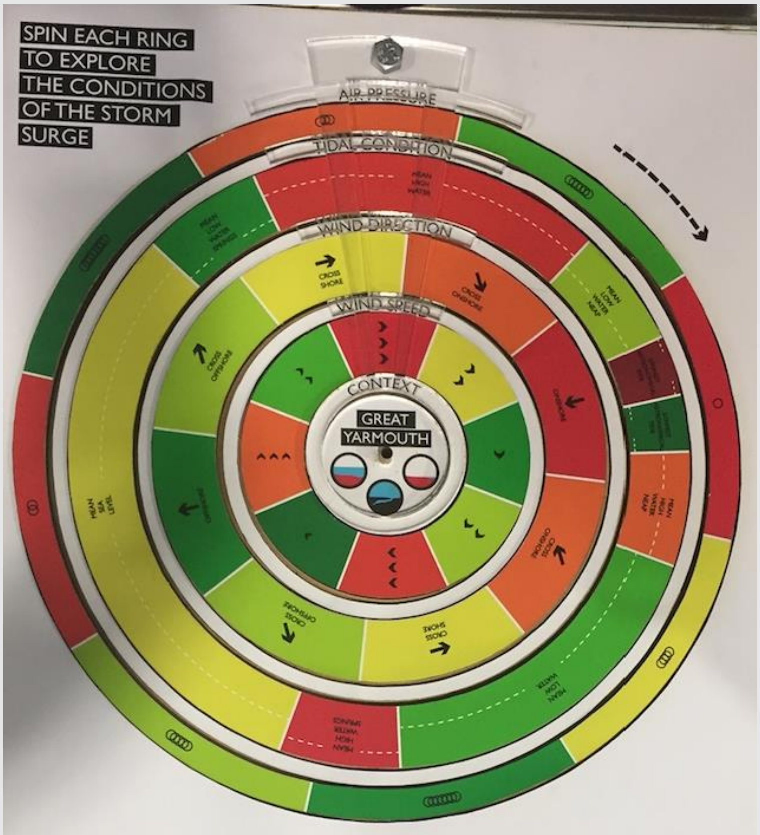
On the Environment Agency website, they display the water levels at each of their gauges, alongside their threshold trigger levels and the highest level ever recorded at that point. This allows people to check and monitor their local area themselves if they have any concerns, as well as identify minor flood risks which would not trigger an automatic warning.



Case study: Coastal flooding and the roulette wheel of doom

One problem with communicating coastal flooding is that the event is contingent on several circumstances happening at once… the 'perfect storm'. For a major coastal flooding event to occur it requires a high tide to be combined with low air pressure and high winds in the right direction. Forecasters therefore have the difficult job of trying to communicate that a potential situation is developing, but that if one factor changes, the whole situation could dissipate completely.

One way to do this, invented by architect Ed Barsley, is to show people a 'roulette wheel' made up of concentric rings, each showing the range of potential possible outcomes for an important factor, and their potential likelihood (by area):



By showing that a flood will only occur when the rings line up with a red sector 'at the top', people can get a sense of the situation.

This was designed as a physical demonstration, but could be adapted as a graphic for broadcasts, where the public can see how aligned factors currently are and hence which to keep an eye on.

7.2. What is known about the effects on the audience?

A systematic review of flood risk communications (Kellens *et al.*, 2013) concluded that theoretical and empirical studies are "nearly non-existent". The few studies that they reported on, along with a handful of others (including qualitative studies) from our own literature search however, are worth considering.

7.2.1. Sources of information

There is evidence that people use information from a variety of sources (such as the media, personal judgement of river levels and rainfall, friends and neighbours) to inform them about flood risks (e.g. (Mileti, 1995); (Creutin *et al.*, 2009)), and prefer information to come from numerous channels (Kreibich *et al.*, 2009). (Kashefi *et al.*, 2009) found that those living in flood-prone areas were extremely proactive in seeking information and showed a high understanding of the risk, but that this was likely due to past experience affecting the perception of the risk. The source of the information and its direct, local, relevance was important to them in terms of trust, and the reason they sought out information from many sources was the concern that floods were such a localised and difficult-to-forecast risk that they expect them to be changeable and for there to be many warnings on which they would not need to act. It has also been shown that people share information amongst their social networks (Coles and Hirschboeck, 2020). In turn, social influences have been shown to be an important factor in affecting people's behaviour during flooding events (e.g. (Becker *et al.*, 2010)(Franklin *et al.*, 2014)). Given these impacts of social influences on flood risk behaviour, (Becker *et al.*, 2015) recommend that communicators develop communications that allow social transmission of information to occur.

One study (Griffin *et al.*, 2008) found that post-event anger at flood management agencies for not doing more to minimise flood risk was a motivator of active information seeking about floods, although they did not report whether the information sought was from alternative sources. Griffin et al. (2008) further found that anger at these agencies was also associated with lower institutional trust. Given trust in flood communications and/or their communicator has been shown to affect intentions to take preparedness actions (Morss *et al.*, 2016), it is possible that people may not take action on the information their anger motivates them to seek out.

Looking for potential ways to increase engagement with flood communications, (Terpstra, Lindell and Gutteling, 2009) examined the effects of a small flood risk communication programme in the Netherlands administered via focus groups that discussed several aspects of flood risk, and workshops that involved both direct (e.g. visits to pumping stations and dyke reinforcement projects) and indirect (e.g. playing board games, listening to fictional flood disaster stories, attending lectures) experience with flooding and flood prevention. Contrary to expectations, the flood risk communication had only a small effect on participants' flood risk perceptions, although the authors posited that this may be a methodological issue whereby there was a mismatch between the measures of risk perception and the contents of the communication sessions.

(Lazrus *et al.*, 2016) carried out interviews about flash flooding with members of the public in Colorado, US, and emphasise the importance of ensuring that the public are aware in advance of what a flash flood might mean in terms of impact, and what to do if it happens, as well as behaviours to avoid in case of a heightened hazard situation (e.g. roads to avoid driving on). This information should be part of any communications when a hazard level is raised. The group's sister-paper (Morss *et al.*, 2015) on their interviews with communications professionals and forecasters highlighted the need (as we saw in our own interviews of storm forecasters) of close working between forecasters and those who would communicate and act on the warnings, in order that everyone rehearsed the procedure and understood what decisions others in the chain are making based on the information being provided.

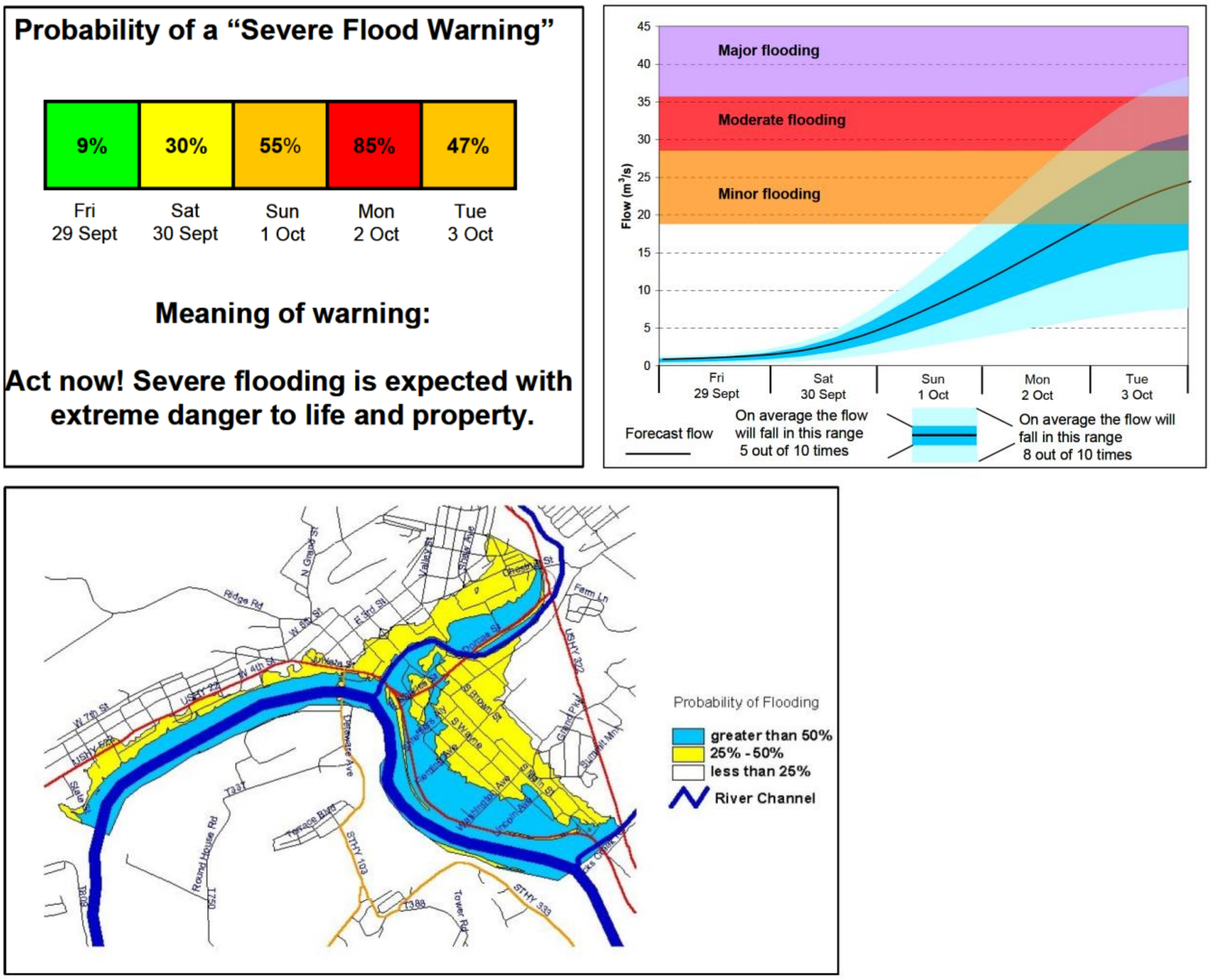
7.2.2. Communicating small probabilities and uncertainty

As discussed earlier in this review, the way in which a number is communicated affects people's perception of risk. There is evidence of this specifically with regards to flood risk: (Keller, Siegrist and Gutscher, 2006) presented people with the same flood risk, presented in a frequency format ("On an average, there is a flood every 100 years") and in a percentage format ("Each year, there is a 1% probability of a flood"), and showed that people perceived the event as riskier when the frequency format was used, echoing results found in other domains. They also examined the effects of providing percentage formats over different time frames, and demonstrated that the 1% in 1 year format was rated significantly less risky than the 40 year or 80 year format. It is notable that there was no difference between the 40 and 80 year ratings of risk however, suggesting this effect is due to an underweighting of small probabilities.

Building on this work, (Bell and Tobin, 2007) go on to illustrate some of the complexities and trade offs in choosing how to communicate flood risk. They examine the perceptions of four flood communications: the 100-year flood, a flood with a 1 percent chance of occurring in any year, a flood with a 26 percent chance of occurring in 30 years, and a flood risk map depicting the 100-year floodplain. Similar to the previous study (Keller, Siegrist and Gutscher, 2006), they demonstrated that people perceived the 100 year flood communication as more concerning than the 1% chance communication, and further than it was more effective in motivating protective behaviour. However, the 1% description was perceived as being more uncertain than the equivalent 100 year flood communication, suggesting that choice of format must involve careful consideration of the key messages the audience wish to receive and the communicator is aiming to convey. Indeed (Handmer, 2001) highlights that one of the key failings in the development and operation of flood warning systems is that they do not centre their aims on the needs of the individuals at risk. For example there is some evidence that people want to know about possible floods, even if it is not certain that it will happen (Brilly and Polic, 2005), implying effective communication of uncertainty may be an important component of flood risk communications.

A review carried out by the UK's flood-related agencies (Kashefi *et al.*, 2009) investigated the possibility of using probabilistic forecasts for flood warnings. At the time of their review, there were no probabilistic flood warnings being used, but they reviewed the limited academic research. They highlighted the usefulness of putting forecast events in context with recent events for the audience.

Kashefi et al drafted potential probabilistic flood forecasts, including one previously drafted by NOAA:



(Source: NOAA 2008).

They then held focus groups to discuss the uncertainty and probabilistic communication. As in other domains, they found that people naturally understood that flood forecasts were uncertain. The 5-day warning with quantitative probabilities (above) was popular because people liked the precision of the numbers and had more impact that simply verbal probability terms. The map (from NOAA) was also liked a lot, although participants preferred the red/green colours of the other graphic. The graph presentation (above) was universally rejected as not clear and showing no useful information.

Several studies have examined public understanding of the watch vs warning terminology used by the US National Weather Service to communicate about flash floods and other hazards such as tornadoes. Several studies demonstrated that the majority of people (although notably not all) are able to correctly distinguish the meaning of the two terms (e.g (Schultz *et al.*, 2010; Ripberger, Silva, Jenkins-Smith, Carlson, *et al.*, 2015; Morss *et al.*, 2016)). Despite evidence that the public understand qualitatively the difference in severity between these two terms however, when ask to quantify the likelihood of a flash flood occurring based on each term, likelihood estimates from the public were lower than the likelihood intended to be communicated by experts, sometimes substantially so (Morss *et al.*, 2016). This in turn was associated with lower anticipated likelihood of responding to a warning by taking protective action (Morss *et al.*, 2016). This indicates a need to attach specific numeric probabilities to verbal terms used, as has been mentioned in several places already in this review.

7.2.3. Use of maps

Maps are a common way of communicating flood risk information, and may serve as a useful tool for maintaining risk awareness even in the (sometimes long) periods of time between flood events ((Hagemeier-Klose and Wagner, 2009). (Hagemeier-Klose and Wagner, 2009) undertook a detailed mixed-methods evaluation of the communication efficacy of flood hazard maps and web mapping services in Germany. They highlighted the diverse needs of user groups that such communications need to fulfil, and recommended the use of a variety of kinds of tailored, local-scale communications to cater to these various needs, not only to achieve the goal of informing but also to create emotional empathy and maintain user awareness between flooding events. They suggest such designs, if implemented, could help to raise flood awareness and knowledge, and encourage information seeking. They also encourage ongoing monitoring and feedback to the various audiences if the communications are to be successful.

They further concluded that most maps are either too simple or too complex. They encourage map designers to carefully trade off simplicity and complexity such as by avoiding technical terms unless it is simply explained, taking advantage of associative information such as using different blue colours to convey water depth, and to create designs which facilitate comparisons with past flooding events. They also make a case for dynamic updating of these communications, linking maps to real-time water level information, and for a gradated labelling of flood risk (such as high, medium and low). The latter fits with the concern that (Smith, 2000) has with flood risk maps; that they do not provide effective communications of the uncertainty in flood forecasts, creating a false absolute in the dichotomy of “flood prone” and “flood free”. Earlier work by (Kates and White, 1961) expresses a similar theme, suggesting that lines on a map, like levees, might produce a false sense of security. These theories, however, have yet to be evaluated empirically (Bell and Tobin, 2007).

8. Best practice in communicating economic & financial forecasts and fluctuations

Unimaginable sums of money flow through our digital financial exchanges and economies every second of every day, with ripples and shockwaves affecting individuals and institutions as meaningfully as any physical, natural disaster.

With huge amounts of money at stake and a fully digital landscape, it's not surprising that considerable investment has gone into visualisation software to help traders see what is happening – and forecast what might happen - to prices through time and across many different stocks (equivalent to geographical spread), or to key economic measures such as GDP.

Most of the stock market visualisations are not forecasts, but real-time information to allow traders to make their own decisions based on their own personal forecasts. National financial institutions, however, do publish economic forecasts.

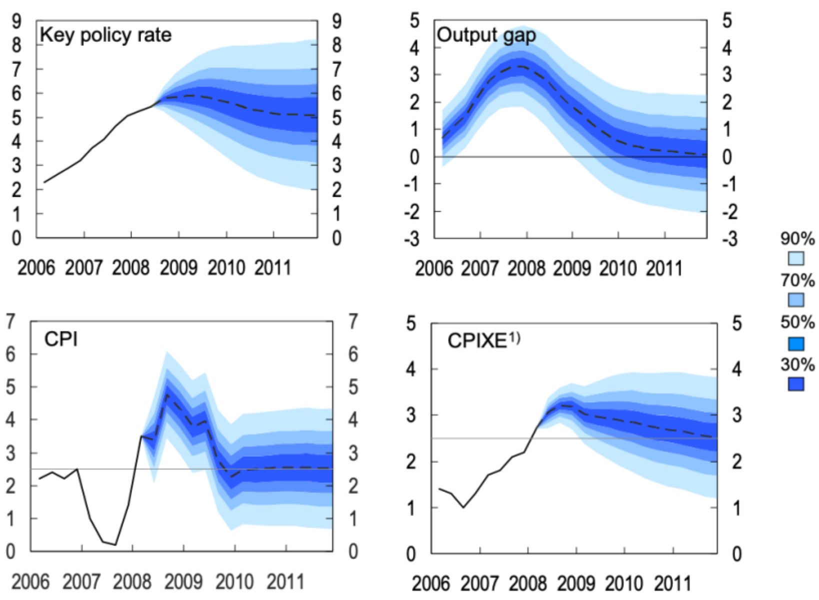
8.1. What is being done in practice

8.1.1. Communicating an uncertain future

Corporate earnings forecasts are usually communicated in text form, and usually including uncertainty as a numerical range (e.g. "the expected earnings for the next period are between $1.15 and $1.25 per share'').

(Holmsen et al., 2008)

Economic forecasts, however, are most commonly done in the form of lines with a fan chart representing uncertainty around the future forecast (and sometimes around past figures that are subject to revisions). The fan captures the quantified uncertainty in the form of different confidence intervals. Although the impetus to move to fan chart presentations by central banks was initially to improve communication and understanding of the range of future projections, the production of them also changed the way that the forecasters within the banks approached their work,

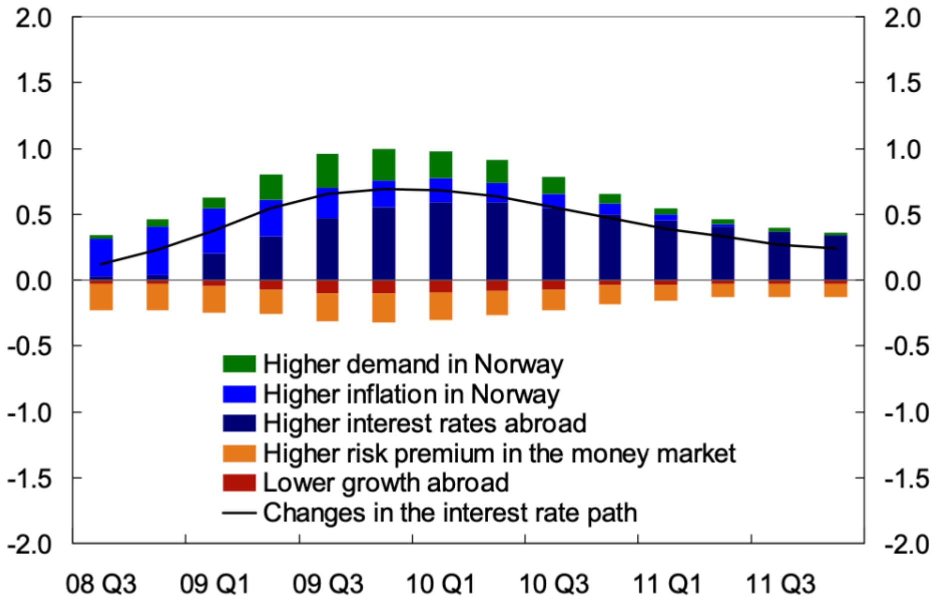


1) CPIXE: CPI adusted for tax changes and excluding temporary fluctuations in energy prices

making them think more about the range of possible outcomes (Britton, Fisher and Whitley, 1998).

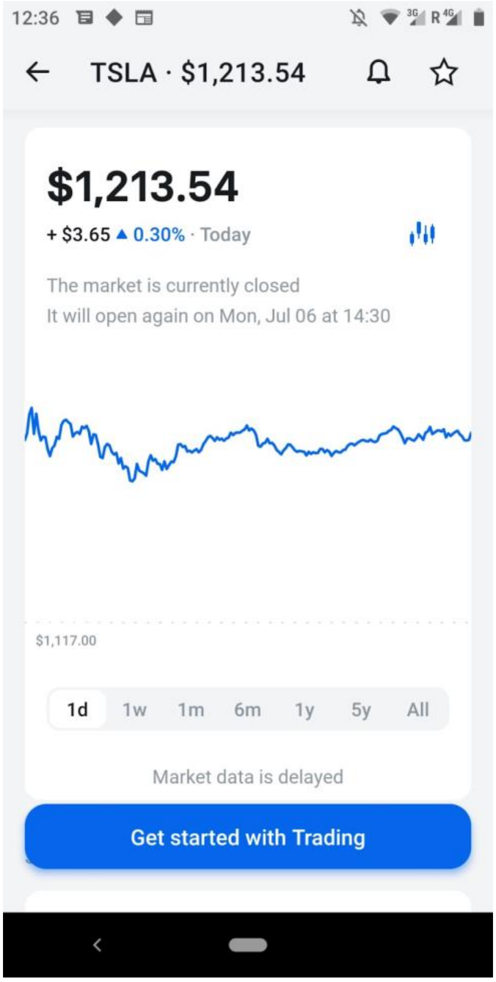
8.1.2. Communicating a dynamic present/past

Norges bank has also experimented with showing how uncertainty in past forecasts has been resolved, showing how the impact of different exogenous shocks to the economic system have resulted in changes to the measure. It is designed to communicate how the bank responds to changing situations and give the audience a better sense of factors that affect uncertainty in the economy (Holmsen *et al.*, 2008):



Norges bank's experimental graphics (Holmsen *et al.*, 2008)

When it comes to stocks and shares, as you'd expect there are simple line graphs showing what is happening over time at one location (to one stock, share, currency price or economic measure).

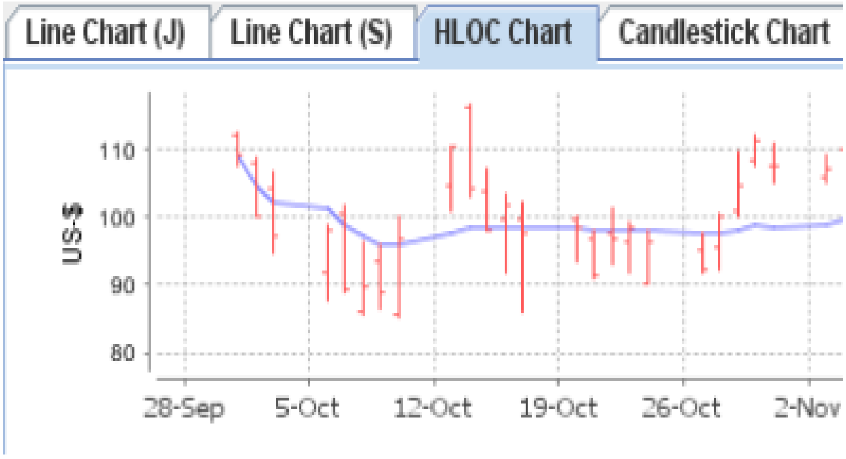


However, finance has also developed a unique format to show daily change at multiple points at once (multiple individual commodities, or multiple timepoints for the same commodity), based on an 18th century way of showing rice prices in Japan. This is the 'candlestick' chart, which shows the opening price, closing price, highest price and lowest price of the day in one 'candle' (the 'real body' of the candle being the difference between the opening and closing price, the colour of the candle representing which direction the change went, and the 'wicks' at either end representing the highest and lowest price of the day). This format therefore communicates 'volatility' over time or another dimension.

It also gives experienced traders an idea of likely future changes, as the patterns revealed by the candles day-to-day show how the direction of travel turns. Of course this is only relevant where such changes follow a pattern (as they tend to in financial markets).

A similar kind of chart is the OHLC (Open-High-Low-Close) chart, which has a vertical line representing the high and the low of the day (like the full length of the candle plus wicks), and little tick marks on the vertical line, left and right, to show the open and close prices.

In addition to this price information, traders may also want to know the 'depth of the market' – the number of other traders currently trying to buy or sell a particular financial instrument - which requires knowing the volume and price of bids, asks and trades dynamically through time. Visualisations incorporating all this information are complex and tend not to be designed for a naïve audience (e.g.(Wright, 1995)).



An interesting addition to these sorts of visual displays in an attempt to help traders understand the patterns in the dynamic data is 'sonification' – turning the patterns into a soundscape, which can be much richer than the visual space possible on a handheld device (Neuhoff *et al.*, 2000; Ben-Tal, Daniels and Berger, 2001).

8.2. What is known about the effects of the communications?

A lot of work has been done in understanding how financial managers create forecasts and choose how to communicate them, but this has mainly been about the degree of precision that they choose to communicate, which is often bound up with increasing credibility and reducing legal liabilities (Du *et al.*, 2011). (Du *et al.*, 2011) found that the audience for financial forecasts was not perturbed by the uncertainty in the communications, because they expected it to be there and expected the precision of the communication to match their understanding of the uncertainty. They also admit that how the audience then interpret and make decisions based on the range is complex (their evidence suggested that they did not choose the midpoint of the range to base their actions on).

The effects of different visual presentations have received much less attention. (Van Der Bles *et al.*, 2019) evaluated public and expert responses to fan charts and gradient plots as ways of communicating uncertainty around past estimates (rather than forecasts), and found that they were broadly well-understood, although the sharp boundaries between the confidence interval bands in the fan were sometimes thought a little confusing and a 'fuzzy fan' approach recommended.

Evaluations of the use of sonic representations alongside visual representations to give enhanced information in a dynamically changing trading situations were mixed (Neuhoff *et al.*, 2000; Keith V . Nesbitt, 2006). In some small experiments it seemed to enhance the perception of direction of change, but sometimes only in one direction. It seems to be an area in need of further investigation as a way of helping those working in a very dynamic and high-pressured, data-driven situation (see (Vickers, 2011) for more).

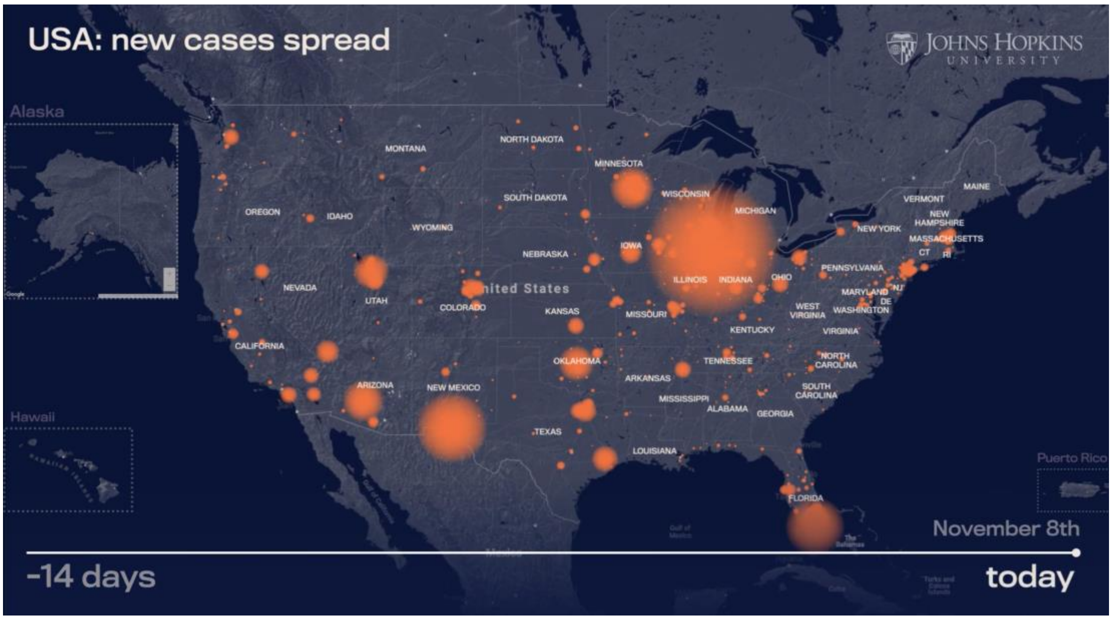
9. Best practice in communicating epidemic and disease risk

As the world has recently become acutely aware, a spreading disease is a risk that is variable in both space and time, with many uncertainties. Computational models in epidemiology are well-recognised and well-used tools and have been instrumental in understanding the temporal growth and geographical spread of infectious diseases like influenza, Ebola and COVID-19.

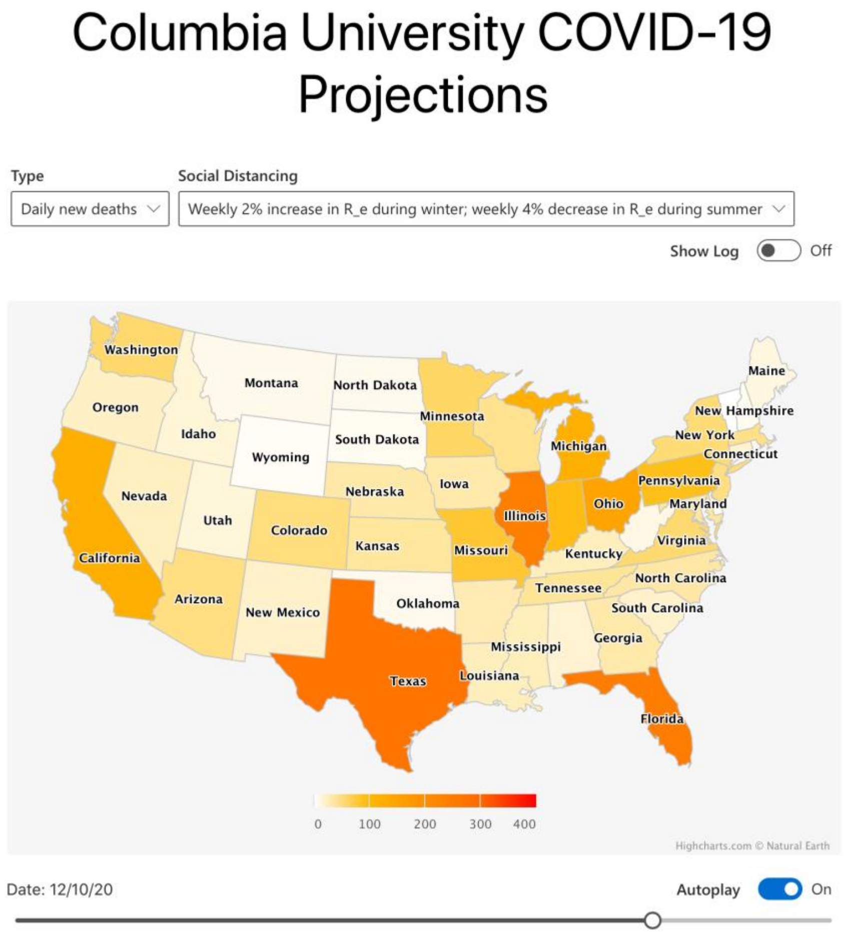
9.1. What is being done in practice

9.1.1. Communicating spatial information

Just like a weather forecast, epidemiological forecasts come in two main forms. One is a map view showing geographical spread, either currently, or as a forecast, which can help public understanding but also policy-level decision making about mitigation measures and emergency health preparations.

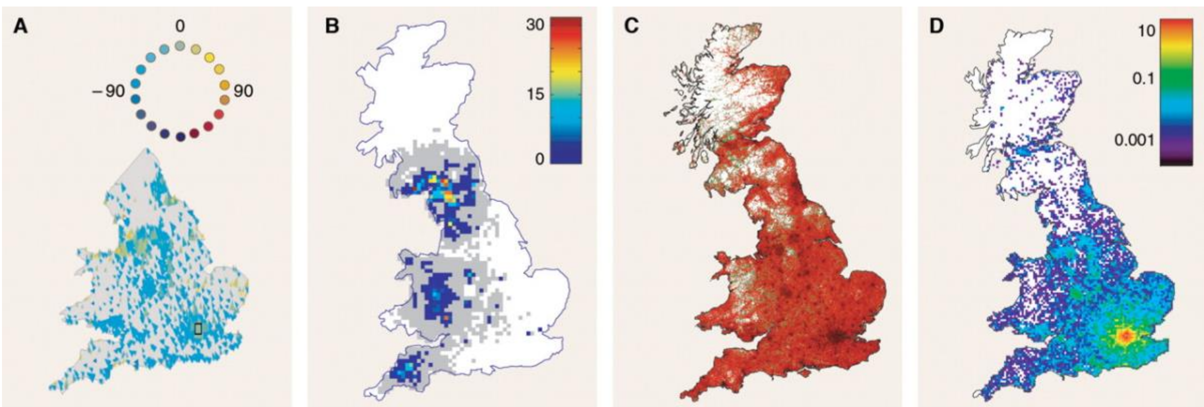


Johns Hopkins animation showing past COVID-19 figures geographically, with 'size of blob' indicating case numbers in each geographical location. The image was animated to show change over time.



A Columbia university forecast of COVID-19 cases showing geographical spread, with the options to vary transmission conditions. Again, this is a still image of an animation.

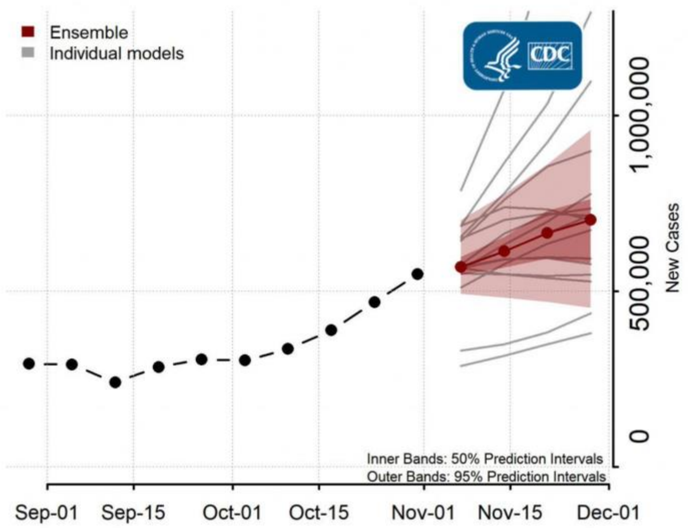
Such maps can be much more detailed, with the models including spatial parameters to better simulate the dynamic spread.



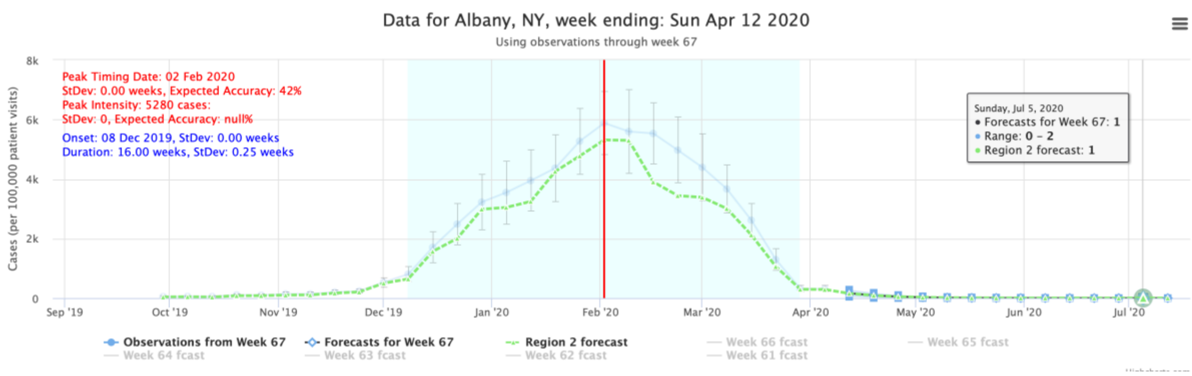
Maps showing modelling of different disease spreads in the UK (pre-vaccination measles, far left; foot & mouth disease, second left; novel influenza, second right; smallpox, far right) from (Riley, 2007).

9.1.2. Communicating temporal dynamics

The second type of epidemiological model forecast is that for a single location, in which case the most common representation of the outputs is a line plot showing potential case numbers. Since ensemble modelling is heavily used, as for many other forecasts, the line charts typically either show the individual component model outputs, or a single summary in the form of confidence intervals around the central estimate.



The US Centers for Disease Control forecasts for COVID-19 cases in the US, showing both the individual model outputs and a summary in the form of a fan chart.

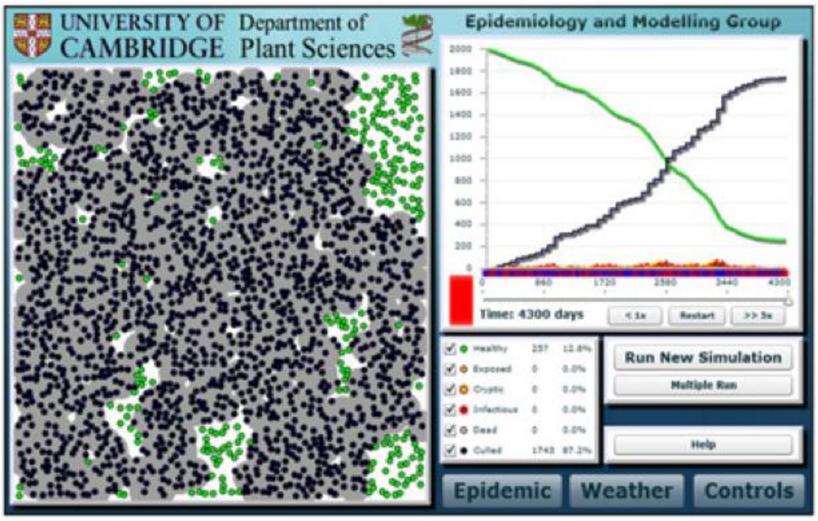


Columbia University's influenza forecasts for Albany, New York showing the predicted timing and duration of the peak alongside expected accuracy estimates of the forecast.

9.2. What is known about the effects of the communications?

Work done after the 2009 H1N1 influenza pandemic investigated the communication of epidemiological forecasts and found, in common with studies into communication around natural disasters, that a key (missing) part was communication between forecasters (modellers) and decision-makers in their study region, Canada (Driedger, Cooper and Moghadas, 2014). By interviewing professionals after the event, they concluded that there was a need to form a 'community of practice' with two-way communication to ensure that decision-makers' informational needs were being met by the modellers and that there were trusted relationships and clear communication of uncertainties and limitations in the models. (Moghadas *et al.*, 2015) then went on to start such a community of practice in Canada, emphasising the need to standardise terminology so that all involved understand each other. Work around HIV modelling and policy decision-making (Delva *et al.*, 2012) came to similar conclusions, making a summary of principles which included 'clear presentation of results, including uncertainty in estimates' and 'clear language' without going into further details of how these should be defined or evaluated.

One group of modellers who appear to have done this is a team from the University of Cambridge who modelled the geographical spread of a plant disease in commercial citrus plantations and potential mitigation actions (Cunniffe *et al.*, 2015). By working with policy-makers, regulators and growers they developed a web interface that visualised potential outcomes from the model in a dynamic way. They did not do a formal evaluation of the interface but report "extremely positive experiences" with non-specialist users.



There appears to be, however, a dearth of work evaluating the effects of epidemiological model communication on their audiences. It may be that the COVID-19 pandemic is the first time such models have been shown to a significant public audience, and so evaluations and new model communication approaches may result.

10. Best practice in communicating seismic forecasts

The 2009 L'Aquila earthquake was one of the most tragic and impactful earthquake events in recent history. The disaster of L'Aquila was originally framed as a failure of seismologists to "predict" an earthquake, however it has become clear that it was actually a failure of risk communication; earthquakes are not just geophysical processes but "socio-political incidents" (Stewart, Ickert and Lacassin, 2018). Thus, identifying the most effective way of communicating seismic risk is key to moving the discipline forward.

In this chapter we concentrate on operational earthquake forecasting: the communication of the probability of a seismic event, possibly alongside its anticipated effects. We also include the context of these forecasts: people's prior risk perception and how the forecasts might affect their behaviour.

As already mentioned, these forecasts – based on measured seismic activity - are highly uncertain, and dynamic in both space and time. The absolute probabilities of any event also remain very low, even if the relative risk (compared to the normal 'background' risk in a given area) can be raised by orders of magnitude.

10.1. What is being done in practice

Earthquake risk communications are disseminated through a wide variety of channels, both formal and informal (Whitney, Lindell and Nguyen, 2004). Most official government messaging is formal in nature, such as public service announcements and brochures (Whitney, Lindell and Nguyen, 2004) that are designed to raise hazard awareness and provide seismic hazard adjustment recommendations (Sorensen and Mileti, 1987), conforming to recommendations based on risk communication research that specific information both about the hazard and what actions can be taken to prepare for it should be included (Mileti and Sorensen, 1987; Tierney, Lindell and Perry, 2001). Whilst many different sources can influence earthquake risk perception (for example (Bahk and Neuwirth, 2000) found that dramatic portrayals of volcanoes in disaster movies had an important effect on people's risk perceptions of them!) it is thought that for most people living in high risk areas, beliefs about earthquakes will be based on information from the media and their peers (Whitney, Lindell and Nguyen, 2004; Heller *et al.*, 2005). This fits with the idea of the social amplification of risk discussed earlier (Renn *et al.*, 1992; Pidgeon, Kasperson and Slovic, 2003; Kasperson *et al.*, 2016).

Only a few countries have so far attempted to give real-time earthquake forecasts to a public or emergency-response audience. Here we feature two of these as case studies, and then discuss the literature evaluating these and other, experimental, communications.

Case study: New Zealand's Operational Earthquake Forecasts (publicly accessible versions)

New Zealand has a website providing public earthquake forecasts for three seismically-active regions of the country; Canterbury, Central New Zealand and Kaikoura (more information and formats were used during the Canterbury earthquake swarm, which are featured in the evaluation section of this chapter). The three forecasts vary slightly in their use of graphics: the Canterbury and Central New Zealand forecasts just show the general area of the forecast on a map, the Kaikoura forecast uses maps to show the area of the forecast and to give information about forecasted aftershock shaking intensity. Whilst the Canterbury and Kaikoura forecasts are OEFs, the Central New Zealand forecast is based on expert elicitation, thus we will focus on the former here. More detail on how these forecasts are made can be found on the GNS Science website: (https://www.gns.cri.nz/Home/Our-Science/Natural-Hazards-and-Risks/Earthquakes/Operational-Earthquake-Forecasting).

The information is generally text and table-based. The Canterbury and Kaikoura forecasts start with a grey box which gives the current forecast in terms of an absolute percentage chance of an earthquake of a given magnitude, and the absolute percentage in the last forecast for the region, with a verbal mention of 'increase' or 'decrease' to highlight the direction of change. Magnitudes are quoted, rather than intensities, because it is thought that people are more familiar with magnitude, even though intensity is of more relevance to them:

"Looking at all the seismic activity in the aftershock area of the November 2016 Kaikōura Earthquake, the expected numbers of earthquakes continue to drop. There is now a 34% chance of one or more M6.0-6.9 earthquakes occurring within the next year, this has decreased from 39% from our last forecast (12 November 2019)."

This is a conscious decision to ensure that the take-home message is clear. The magnitude is stressed because it is a common misconception that the magnitudes of aftershocks decrease, whereas it is the likelihoods, given a certain magnitude that change (meaning that a high magnitude event remains possible).

This is followed by a table indicating the absolute probabilities of one or more earthquake of a given magnitude, the average number of earthquakes of a given magnitude, and the range of the possible number of earthquakes of a given magnitude, all given 'within one year' (although during a seismically active period, this time period is reduced). Absolute probabilities are used so as to avoid potentially alarming relative risks during seismically active periods. This is followed by a verbal explanation of the table, sometimes giving verbal indicators of the probabilities.

Canterbury table:

Canterbury aftershock sequence long-term probabilities

	M5.0-5.9			M6.0-6.9			M≥7.0		
	Average number	Range	Probability of one or more	Average number	Range	Probability of one or more	Average number	Range	Probability of one or more
Within 1 year	0.5	0 - 2	38%	0.04	0 - 1	4%	0.005	0 - 1	<1%

Issued on 1 September 2020. This table shows a forecast for future aftershocks for1 year from 1 September 2020, for the area from 171.6-173.2 degrees east and 43.3-43.9 degrees south (see map).

This table says that:

- Within the next year, there is a 38% probability (unlikely) of one or more earthquakes of magnitude 5.0 to 5.9 occurring in the area shown in the box in the map. It is expected that there will be between 0 and 2 events of this magnitude within the next year.
- It is very unlikely (4%) that there will be a magnitude 6.0-6.9 earthquake.
- It is extremely unlikely (less than 1%) that there will be an earthquake of magnitude 7 or greater.

New Zealand's Operational Earthquake Forecasts cont'd

Kaikoura table:

	Average number of M5.0-5.9	Range* of M5.0-5.9	Probability of 1 or more M5.0-5.9	Average number of M6.0-6.9	Range* of M6.0-6.9	Probability of 1 or more M6.0-6.9	Average number of M≥7	Range* of M≥7	Probability of 1 or more M≥7
within one year	4.8	0-13	91%	0.5	0-2	34%	0.04	0-1	3.7%

Forecast for rectangular box (see map below) with the coordinates -40.7, 171.7, -43.5, 171.7, -43.5, 175.5, -40.7, 175.5 at 12 noon, Monday 9 November 2020; 95% confidence bounds.

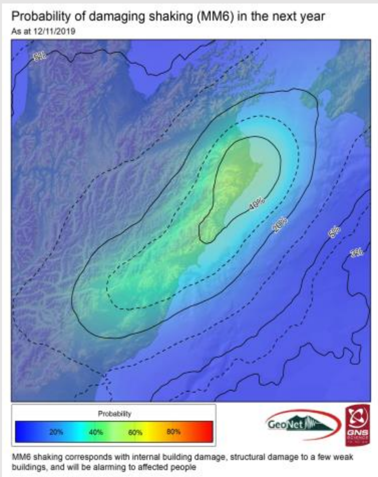
The aftershocks of the magnitude 7.8 Kaikoura earthquake are mostly occurring throughout a broad area from North Canterbury through to Cook Strait that surrounds the faults that ruptured in that earthquake, although a few have occurred in the lower North Island. We forecast aftershock probabilities for the area in the red box on the map below. The area near the centre of the box (around Kaikoura) is more likely to experience felt aftershocks than areas towards the edge of the box. See the MMI map below for more information on the forecast shaking. Earthquakes can and do happen outside this box but the box represents the most likely area for aftershocks in this sequence.

For example, there is a 34% chance of one or more M6.0-M6.9 within the next year. We estimate there will be between 0 and 2 earthquakes in this magnitude range within the next year.

The current rate of M6 and above earthquakes for the next year is about 1.5 times larger than what we would normally expect for long term seismicity represented in our National Seismic Hazard model. As the aftershock rates decrease, this difference will decrease as well.

Verbal estimates given are always accompanied by numbers as is advised (and New Zealand experienced communication problems during an event when geoscientists used verbal terms and emergency managers did not know what they meant).

As mentioned above, Kaikoura's forecast also has a map illustrating forecasted probabilities of shaking of particular intensities:



Other measures, such as peak ground acceleration, are used only for technical audiences.

The pages are only updated when there is a change to the information (i.e. after seismic activity). This means that sometimes the information is a year old.

Case study: US Geological Society's Operational Earthquake Forecasts

USGS started using earthquake forecasting publicly in 2018, releasing aftershock forecasts from around an hour after a mainshock in Anchorage, Alaska, updated over days, weeks and months. They also learnt from experience in New Zealand and Nepal and interviews with potential expert users. After feedback from emergency responders and monitoring media coverage they adapted their template to avoid misunderstandings.

The template is designed to have layers to allow increased depth of information. The forecasts are placed online and are designed to have a title with the main message: "Aftershock Forecast. Be ready for more earthquakes. Our model of the expected numbers and odds of future earthquakes."

The first tab is entirely text-based. It specifically keeps to a single defined time period, to avoid confusion, alongside observed history (how many shocks have already been observed at the location). Then a series of bullet points showing the expected number of earthquakes of different magnitudes over different timepoints.

A second tab shows two tables, one showing the probability and one showing the likelihood of earthquakes of different magnitudes. The third tab shows the parameters used in their modelling.

Commentary | **Forecast** | Model

Note: The expected rate of earthquakes continues to decline throughout the time windows. The probabilities in the longer time windows are higher only because the rates are being summed over a longer time period. These longer periods may be useful when planning recovery and rebuliding projects.

The probability of at least one aftershock of at least magnitude M within the given time frame. Forecast starting 2019-11-30 18:00:00 (UTC)

	1 Day	1 Week	1 Month	1 Year
M ≥ 3	21 %	81 %	> 99 %	> 99 %
M ≥ 5	< 1 %	2 %	7 %	48 %
M ≥ 6	< 1 %	< 1 %	< 1 %	6 %
M ≥ 7	< 1 %	< 1 %	< 1 %	< 1 %

The likely number of aftershocks of at least magnitude M within the given time frame. Forecast starting 2019-11-30 18:00:00 (UTC)

	1 Day	1 Week	1 Month	1 Year
M ≥ 3	0 to 2	0 to 5	3 to 13	47 to 86
M ≥ 5	*	*	0 to 2	0 to 3
M ≥ 6	*	*	*	0 to 2
M ≥ 7	*	*	*	*

* Earthquake possible but with a low probability.
Likely number of aftershocks is the 95% confidence range.

US Geological Society's Operational Earthquake Forecasts cont'd

They try to explicitly use 'empathetic' messages: "USGS scientists know that there will be more aftershocks, and some will be larger than others, but these will decrease in frequency over time. USGS scientists do not know the exact time, location, and magnitude of any specific earthquake. The USGS family also knows that earthquakes can be upsetting for people and will continue to provide information to help people stay safe and care for themselves and each other." (Becker et al., 2019, had reported participants as saying that the wording tested in New Zealand's forecasts was 'too clinical').

An addition requested by the media and public was a likely duration for the period of the earthquake sequence.

10.2. What is known about the effects on the audience?

Although there is very little work specifically on the evaluation of operational earthquake forecasts, we here briefly review the academic work that has been done that might be of relevance to understanding the effects of communications of such forecasts first, and then the specific work done on OEF.

10.2.1. Awareness & risk perception of seismic events

As might be expected from the complexities of human responses to natural hazards and disasters in general, the link between earthquake hazard awareness, risk perception and seismic hazard adjustment is not always straightforward (Marti *et al.*, 2018). As previously mentioned, risk perception is a core feature of both protection-motivation theory (Rogers, 1975) and the protective action decision model (Lindell and Perry, 2012), and in accordance with these frameworks has been shown to be a significant predictor of seismic hazard adjustment (e.g.(Kunreuther *et al.*, 1978; De Man and Simpson-Housley, 1987; Palm *et al.*, 1990; Dooley *et al.*, 1992; Mileti and Fitzpatrick, 1992; Lindell and Prater, 2000)). The strength of these relationships is often weak however (Solberg, Rossetto and Joffe, 2010) and there are several examples of studies that have shown no relationship between the two variables at all (Jackson, 1981; Russell, Goltz and Bourque, 1995; Mileti and Darlington, 1997a). Thus, whilst communications aimed at raising risk perceptions may go some way to encouraging seismic hazard adjustment, earthquake communicators should consider approaches that target seismic hazard adjustments directly (see below).

Solberg, Rossetto and Joffe (2010) suggest that part of this variation in study results may be due to demographic differences between them that moderate the risk perception-hazard adjustment relationship. However, it is also worth noting that risk perception is a multifaceted concept including cognitive, affective and socio-cultural components (e.g. (Douglas and Wildavsky, 1983; Loewenstein *et al.*, 2001; Joffe, 2003; van der Linden, 2015) Part of the disparity between these studies then, may be because they measure different components of risk perception. For example, although knowledge and thus awareness of earthquakes is one of the cognitive components of earthquake risk perception, several studies have highlighted the disconnect between awareness of earthquakes and the personalisation of that risk (Jackson and Mukerjee, 1974; Turner, Nigg and Paz, 1986; Mileti and Fitzpatrick, 1993; Mileti and Darlington, 1995), and it is that personalisation of the risk that taps into the affective dimension of risk perception. Thus, studies using variables such as earthquake awareness or earthquake likelihood as proxies for risk perception may yield different results when evaluating its relationship to seismic adjustment than studies that use a more affective measure, like experience with or worry about earthquakes. Future work would do well to create a more holistic measure reflecting all these components, and to evaluate its relationship to seismic hazard adjustment.

10.2.2. Communicating small probabilities

As with many other risks, the way in which numbers are presented in communications about earthquakes has been shown to affect people's interpretations of them. There have been many studies examining framing effects with regards to earthquake communications, where logically equivalent but differently phrased statements can yield different risk perceptions (Henrich, McClure and Crozier, 2015). (McClure, White and Sibley, 2009) examined the effects of framing communications about both the outcome of an earthquake event (experiencing harm or avoiding harm) and the proposed preparedness actions (taking or not taking action), on both general earthquake preparedness actions and more specific actions (such as buying a battery powered radio). They found that negative framing of the earthquake outcome increase willingness to engage in both general and specific preparedness actions, whilst positive framing of the action itself compounded this effect for specific preparedness actions. In a follow up study however, (McClure and Sibley, 2011) this interaction was in the opposite direction; negative framing of both outcome and action yielded the highest intentions towards specific preparedness actions. (Marti *et al.*, 2018) posit that this may be because the influence of the individuals' risk perceptions and their affective state (positive or negative) was not considered, despite studies in other disciplines finding both to be an important moderator of the effects of message framing (Keller, Lipkus and Rimer, 2003; Chang, 2007).

(Marti *et al.*, 2018) went on to examine for the effect of this three-way interaction between affect, risk perception and framing on Swiss homeowners' attitudes towards general precautionary measures towards earthquakes. They demonstrated that only in combination did these factors influence attitudes. Specifically, a message that induced negative mood, contained high risk information and used positive framing induced the greatest degree of attitude change, although messages that combined induced negative mood, low-risk information and a loss-frame, and those that combined induced positive mood, low-risk information and gain-framed messages also had a significant impact on participants' attitudes.

Studies have also examined other ways in which numbers in earthquake communications can be presented that may affect people's perceptions, such as varying the time frame over which the risk is presented, or expressing outcomes in terms of frequencies. (Henrich, McClure and Crozier, 2015) tested five statements that were logically equivalent but that used different formats for presenting the risk. They found that the statement "There is a 10% chance in 50 years that 1600 people are killed." was perceived as being the most risky.

The outcome (1600 people killed) was the largest number of the options given, achieved by using a longer time period over which the risk was considered (as opposed to a yearly risk), and yet the '10% chance in 50 years' made the time frame sound more tangible (i.e. possible within a person’s lifetime) than 'once every 500 years', one of the alternative phrasings tested. All these types of study highlight the importance of considered design and evaluation of communications about earthquakes that take account of these potentially powerful nuances in presentation of numbers.

10.2.3. Communicating spatially dynamic information

Maps are a popular way of communicating information about earthquakes (Gaspar-Escribano and Iturrioz, 2011). Currently they are not used to a large extent in operational earthquake forecasting, but they are often used in the form of hazard maps, which are the commonest way of visualising long term, seismic hazard (Marti, Stauffacher and Wiemer, 2019). Hazard maps are typically designed for primary, expert users (Perry *et al.*, 2016a) who might include geologists, seismologists and civil engineers and who are very familiar with seismic hazard maps (Marti, Stauffacher and Wiemer, 2019). There are other users who are less familiar, such as other professionals (e.g. insurance professionals, architects), emergency responders, policy makers and the general public (who, for example, might use such maps to inform decisions about whether to buy a house in a particular area or whether to purchase earthquake insurance). However the hazard maps are typically communicated in a from unaltered from that designed for expert users (Thompson, Lindsay and Gaillard, 2015; Marti, Stauffacher and Wiemer, 2019).

Shakemaps are another common type of map in seismology, developed originally by the USGS and used to portray the extent and severity of ground shaking after an earthquake has occurred (Wald *et al.*, 1999, 2006, 2008). Again, shakemap users are typically experts including seismologists and geologists, but other key audiences are emergency responders and risk managers. Shakemaps are also used by the general public.

Studies that have empirically evaluated the efficacy (in terms of comprehension), trustworthiness and actionability of these hazard and shake maps for their users could inform the design of maps for use in communicating dynamic seismic information, such as that from operational earthquake forecasts. General map design as a tool for representing temporally and spatially dynamic risk was discussed earlier, but not all of this work is empirically evaluated. Whilst expert based insights can be incredibly useful, some commonly used formats and features can have been maintained through status quo (e.g. use of proportional circles to represent different magnitudes). Thus evaluation is a very important component of map (and indeed most!) communication design. Whilst several studies have empirically evaluated the efficacy of maps and map-based visualisations for other natural hazards (e.g. (Hagemeier-Klose and Wagner, 2009; Fabrikant, Hespanha and Hegarty, 2010; Hegarty, Canham and Fabrikant, 2010; Thompson, Lindsay and Gaillard, 2015; Ruginski *et al.*, 2016; Padilla, Ruginski and Creem-Regehr, 2017), there appears to have been a lack of empirical evaluation of maps used to communicate information about earthquakes. One notable exception is (Marti, Stauffacher and Wiemer, 2019), who provide a novel evaluation of seismic hazard maps as tools for communication with non-expert users, including architects and engineers who do not specialise in seismic retrofitting, and the general public.

Using the three different map types (hazard map, magnitude map and effects map) used by the Swiss Seismological Service (SED), (Marti, Stauffacher and Wiemer, 2019) took a mixed-methods approach to evaluate user comprehension of each map type, including understanding of statistical information provided in statements. They also evaluated the value of interactive content in facilitating comprehension. They found that most participants were able to distinguish hazardous from less hazardous areas using the seismic hazard map, although comprehension was significantly related to participant numerical ability, with high numeracy participants performing better. This particular map had been designed, where possible, in line with best practice from the literature on visualisation of other hazards, such as using darker colours to depict higher hazard areas and ensuring legends are prominently positioned and contain numeric and qualitative information (Gaspar-Escribano and Iturrioz, 2011). This suggests that despite evaluations of hazard maps from other disciplines showing they are ill-understood by the lay-public (Hagemeier-Klose and Wagner, 2009; Severtson and Vatovec, 2012; Kjellgren, 2013; Perry *et al.*, 2016b), they may in some instances be informative provided they are well designed. (Marti, Stauffacher and Wiemer, 2019) also demonstrated that participants were less successful when interpreting magnitude and effects maps, which had not been so closely based on best-practice (for example they had fairly low contrast ratios, which are thought to reduce readability and comprehension (Hagemeier-Klose and Wagner, 2009; Kunz, Grêt-Regamey and Hurni, 2011)), and conclude that these maps should be redesigned to improve performance, perhaps being co-produced with the relevant users.

In looking at participant interpretation of statistical information, (Marti, Stauffacher and Wiemer, 2019) found that the majority of participants (73.3%) were able to correctly interpret a statement describing an event as occurring "within" a certain period of time i.e. they understood that the event could occur at any point during that time window. Again, there was a positive relationship between performance and numeracy, and risk perception was found to moderate performance too. Finally, based on their smaller sample of architects and engineers they concluded that SED map interactivity in its current form did not facilitate participant comprehension. (Marti, Stauffacher and Wiemer, 2019) finished by highlighting the importance of not only evaluating current hazard communication products, but also exploring and evaluating alternative products for raising risk awareness and preparedness.

10.2.4. From awareness to action

One of the desired outcomes of earthquake communications may be to raise seismic hazard adjustment, which we define here in accordance with (Solberg, Rossetto and Joffe, 2010) as "all types of actions and behaviours undertaken by individuals and households that have the capacity to either reduce immediate risk of damage and loss during an earthquake, or to prepare for post-impact conditions that might adversely affect survival probabilities". Indeed, given the impossibility of predicting the precise timing, location and consequences of future earthquake events, proactive preparation is an important component in reducing the amount of damage and fatalities from an earthquake event (Paton and Johnston, 2001; Paton *et al.*, 2015), and appropriate behaviour by both communities and individuals affected by earthquakes has the potential to mitigate impact substantially, reducing the burden on emergency response (Marti, Stauffacher and Wiemer, 2020).

Frequent education and awareness campaigns are critical to increasing levels of preparedness for natural disasters (Kapucu, 2008). As already noted however, simply providing information in isolation to raise hazard awareness or risk perception may be insufficient to cause behaviour change (Heller *et al.*, 2005; Marti, Stauffacher and Wiemer, 2020). A recent review by (Marti, Stauffacher and Wiemer, 2020) identified just ten campaigns evaluated and written up in the literature that had targeted the public and focused on their behaviour and on disaster preparation generally (as of November 2018). Eight of these focused on the US (Mileti *et al.*, 1991; Mileti and Fitzpatrick, 1992; Mileti and Darlington, 1995; Tanaka, 2005; Blakley, Chen and Kaplan, 2009; Wood, 2013; Perez-Fuentes, Verrucci and Joffe, 2016; Adams *et al.*, 2017), one on New Zealand (Becker *et al.*, 2016) and one on Israel (Shenhar *et al.*, 2015). (Marti, Stauffacher and Wiemer, 2020) note that traditionally, such campaigns were mainly based on printed products such as brochures, however they have moved more recently to include video, animation and online communication, including social media. Although there is some evidence that people pay less attention to channels such as social media than they do to more traditional sources of information (Becker *et al.*, 2016; Adams *et al.*, 2017), recent work by (McBride *et al.*, 2019) suggest that social media communications could be an important tool for scientists and scientific organisations in the influence they have on the narrative developed by the mainstream media and in turn broadcast to the public during a disaster. Examining the information sources used by US media during the Bombay Beach earthquake swarm in 2016, (McBride *et al.*, 2019) showed that the media used a combination of information sources including social media, as it provided rapid information about the dynamically changing situation, and that this interaction between news media and social media continued even as the swarm in Bombay Beach slowed. McBride et al. (2019) go on to caution, however, that the media were less linguistically precise in their reporting of communications from scientists.

The studies identified by (Marti, Stauffacher and Wiemer, 2020), and others associated with them, do provide some insights into the effects of the campaigns in question. For example (Mileti and Fitzpatrick, 1992, 1993) found that the preparedness campaigns for the Parkfield Earthquake Prediction Experiment in the US affected recipients' risk perceptions, and in turn that these raised risk perceptions related to increased information seeking behaviour. The retention of information about earthquake hazard included in these communications however was found to be poor (Mileti and Fitzpatrick, 1993)), and most of the behavioural recommendations that were adopted were those that had been recommended for many years rather than the more novel suggestions that the brochures communicated (Mileti and Darlington, 1997b), perhaps speaking somewhat to a disconnect between risk perception and seismic hazard adjustment. (Whitney, Lindell and Nguyen, 2004) suggest that part of the reason for this is that people who live in earthquake risk areas might believe they already know all the necessary information about earthquakes, and thus do not need to attend to this additional information. They also comment that most risk communications about earthquakes follow the knowledge-deficit model of risk perception, which, as previously discussed, is flawed. These studies also demonstrated that the relationship between risk perception and information seeking was strongest in those who knew others who had engaged in protective behaviours, and who had received a variety of risk messages. Another example of the value of multi-channel communication comes from (Tanaka, 2005) who demonstrated that risk perceptions of earthquakes in a US and Japanese sample were higher in those who had received information about them via multiple channels. Nevertheless, after thorough review of the ten campaigns they identified, (Marti, Stauffacher and Wiemer, 2020) concluded that they provide little *empirical* evidence on which future campaigns can be based.

Drawing on work from other disciplines, (Marti, Stauffacher and Wiemer, 2020) outline some key recommendations for the design and communication of earthquake preparedness campaigns. These are worth reading at length in the paper, but we quickly summarise some standout messages here. Firstly, they highlight the need for regular and repeated communication, as discussed in the context of earthquake communications by (Tanaka, 2005; Shenhar *et al.*, 2015), and suggest that regular training of the audiences for the communications should be a component of this. They also note the importance of training risk communicators and integrating them into campaigns as much as possible. Secondly, they emphasise the importance of knowing the characteristics of the audience for the communications, and their personal context, particularly regarding the relevance and practicality of implementation of recommended actions. The information an audience wants and the capabilities for implementation they have can often differ from that which experts assume (Steelman *et al.*, 2015). This speaks to the value of audience participation in the design of communications about earthquakes (Stewart, Ickert and Lacassin, 2018). Finally, (Marti, Stauffacher and Wiemer, 2020) highlight the vital importance of evaluating preparedness campaigns to ascertain things like their impact on target audiences or the longevity of any behaviour change they may promote. Although this may involve upfront cost, if careful design and evaluation helps ensure the success of a campaign, less money will be wasted on campaigns of low efficacy. Indeed (Marti, Stauffacher and Wiemer, 2020) comment that “Professionally designed and evaluated campaigns are essential for ensuring that individuals can make use of faster, more accurate warnings based on sophisticated risk assessments.”

10.2.5. The challenge of misinformation

(Whitney, Lindell and Nguyen, 2004) carried out a survey into earthquake knowledge and belief in earthquake myths in Californian students, and went on to show that corrections of these myths were more effective when they used a “Earthquake myths versus facts” format, where myths and facts were presented alongside each other, than when they used a format that detailed earthquake facts alone.

Rumours and misinformation can also spread damagingly after an event. (Takayasu *et al.*, 2015) followed one such rumour on Twitter after the Great East Japan Earthquake in March 2011, warning that contaminated and dangerous rainfall was expected after a chemical explosion caused by the earthquake. From one user, 38,226 others were soon disseminating the information. However, by 15 hours after the rumour started, correction tweets equalled rumour tweets, and 21 hours after it started, The City Hall of the locality of the explosion sent a correction tweet directly to 15,000 followers stating “*After the LPG tanks explosion, there are rumors that harmful chemically contaminated rain may fall. However, the Earthquake Disaster Prevention Division of the City Fire Department confirmed that there is no scientific basis for these rumors. Please be careful not to be confused by the rumors*”. In the end 56,818 users spread the correction and half were directly traceable to the City Hall tweet. Again, mentioning the myth and responding with trustworthy authority worked.

10.2.6. Communication of Operational Earthquake Forecasting

Several studies have suggested that OEF can be used to motivate populations to take protective action against earthquakes (Jordan *et al.*, 2011, 2014; Jordan, 2013b; Field *et al.*, 2016). However, OEF has significant challenges over and above those of communicating the long-term seismic hazard which has been the focus of much of the research mentioned above.

What information do audiences want?

An important component of all communication is knowing your audience's needs. Some general conclusions about the types of information different audiences need during an aftershock sequence were drawn by (Becker *et al.*, 2019) researching the Canterbury earthquakes in New Zealand. They carried out focus groups and interviews with 55 participants (public, media professionals, insurance professionals, infrastructure managers and emergency responders). There was support for a variety of information formats, highlighting the need for this information to be communicated in a variety of different ways (e.g. maps, tables, text, graphs, probabilities, rates, analogies), although each needed to be set within a context to ensure relevance of the information to the varied audiences using it (Becker *et al.*, 2019). Another request was for information on what to do during the aftershock sequence, including protective actions people could take (Becker *et al.*, 2019). We reproduce the table of the information requirements mentioned by both experts and public below:

Science information	Protective action information	Coping/recovery information
• What had caused the earthquakes (including geological background) • Likely future earthquake locations • Likely future magnitudes or intensities of aftershocks (e.g. *"the aftershocks may be [felt as] as severe[ly] as the initial shock"*) • To know there will be aftershocks • Duration of the aftershock sequence (e.g. "*another six months*"; *"When's going to be the next one?"*) • Context around an aftershock forecast (how it compares to background seismicity, what happened in previous NZ and overseas earthquakes, how do future earthquakes relate to what we have already just experienced?) • Aftershock information to inform longer term decision-making (e.g. future property purchases).	• How to immediately respond to aftershocks (e.g. Drop, Cover, Hold) • What to do next during the aftershock sequence (e.g. look after your friends/family). • How to get prepared (e.g. physical preparedness, develop a family emergency plan).	• Getting to and from school for parents • Commuting to and from work • Whether their house would be liveable • Advice on how to cope with aftershocks.

The information that members of the public requested from OEF, from (Becker et al., 2019)

Sector	Information needs	Uses
Urban Search and Rescue (USAR)	• Details of earthquakes that had just occurred (e.g. earthquake spectra) • Aftershock forecasts (size, number of earthquakes, location) • Likely consequences	• To determine when it would be 'safe' enough to re-enter buildings to save lives
Structural engineers/building assessors	• Details of earthquakes that had just occurred (e.g. earthquake response spectra) • Aftershock forecasts (magnitude, probabilities, number of earthquakes, location) • Likely consequences	• To provide context for likely damaged buildings and how to deal with them (e.g. earthquakes of M5.5 that had occurred were used as a threshold[a] for shutting the Red Zone down) • To determine when it would be 'safe' enough to re-enter buildings for assessment, and how to "sticker" them (Green – no restrictions, Yellow – restricted access, Red – unsafe do not enter)
Geotechnical engineers	• Details of earthquakes that had just occurred (e.g. fault location, orientation and nature of rupture. Peak Ground Accelerations (PGA)). • Aftershock forecasts (probability, size, number, timeframe, decay rate)	• To provide context, so they could make judgements about the likely evolution of aftershocks, and the risks they might pose • To inform risk models (e.g. liquefaction, landslide risk)
Critical infrastructure providers	• The probability of larger earthquakes (i.e. size), and the timeframe in which these might occur. • Likely consequences (e.g. liquefaction)	• To prepare resources (e.g. size of labour force needed) and develop relationships for response to potential aftershocks. • Determine repair scope, timing and standard of infrastructure repair.
Emergency managers and responders	• General information about an earthquake that had occurred (e.g. M, location, depth, time, what had caused the earthquakes, etc.) • Aftershock forecasts (probability, size (M and MM), number, location, and timeframe (including timeframes related to immediately after a large earthquake (6–12 h), within 7 days and up to 1 month)) • Likely consequences (e.g. risk of building collapse)	• To determine risks in a fragile building environment • To decide where to place cordons around dangerous buildings/ infrastructure, how long to keep those in place, and how to control the entry and exit of people • To decide when to stop people entering buildings (e.g. for building assessment); and when it would be 'safe' to re-enter • To determine risks related to building demolitions • To inform the public about aftershocks and answer questions such as, "Will there be more aftershocks?", "When?" and "What will the impact be?"
Communication representatives	• General information about an earthquake that had occurred (e.g. M) • General aftershock information	• To inform how they would respond to an earthquake that had just occurred (e.g. evacuate; check buildings). For example, M5 was used as a threshold for checking "certain things in […] buildings" • To inform what they would tell people about what had just happened, and what might happen in future
Business representatives	• General aftershock information (e.g. probability, size, timeframe) • Likely consequences	• To inform businesses' decisions about whether they could re-enter their buildings • Specific industries like tourism used forecasts to brief the tourism industry about potential aftershocks, develop messages about the city's damage and safety, and promote the return of tourists
Construction mangers Insurers	• General aftershock information • Aftershock forecasts (e.g. probability, size, number, location, timeframe, decay). They specifically wanted to know: • When damaging earthquakes were going to cease (i.e. aftershock duration) • "Aftershock likelihood combined with ground conditions" (Scientist, K) • "Short, medium and long-term pictures" (Emergency manager and insurance representative, R) e.g. up to 1 year • When the aftershock rate had decayed beyond a certain threshold • Where past events had occurred for decision-making context • Likely risks and consequences	• To evaluate the risks of building demolitions. • To inform timing for repairs, rebuild and/or write-offs • To decide when insurers could begin insuring again • To understand whether properties could be insured • To decide the level at which insurance premiums should be set
Policymakers	• Aftershock forecasts (e.g. size, number, timeframe) and specifically the forecast 50-year decay rate	• To devise a local building standard that would be applied in the Canterbury rebuild
Recovery leaders	• Aftershock forecasts (e.g. size, number location, timeframe (with suggested timeframes of 1–5 years, though to decades) • When the aftershock rate had decayed beyond a certain threshold	• To decide when to commence with repairs and recovery • To delineate red zones for land retirement and remediation

[a] Thresholds are mentioned throughout people's discussion with respect to making decisions about response (e.g. use of thresholds to determine when to stay out or enter a dangerous area; when to check buildings/infrastructure) and recovery (e.g. when to begin repair and recovery).

The information that expert user groups requested from OEF, from (Becker et al., 2019)

Both expert groups and the public desired a variety of different forms of information about aftershocks, from basic information about what aftershocks were to help improve knowledge and contextual understanding, to more technical scientific information used by agencies to help inform complex decision making. As can be seen from the tables, they often requested information about durations and expected timings (Wein *et al.*, 2016; Becker *et al.*, 2019). They also asked for the information to be personalised to 'what this means for them' – what they might expect as a result.

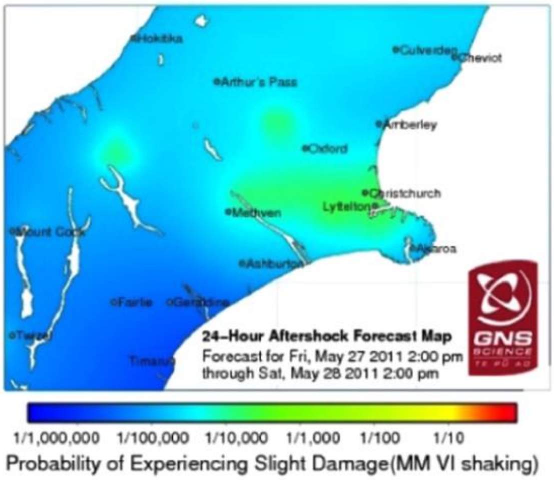
Becker et al. (2019) also highlighted the fact that many people were unaware of the availability of official seismic forecasts, and were using unofficial information as a result. When shown the information, they found it useful to be able to compare the forecast risks with those from both background seismic levels and previous earthquakes in New Zealand and elsewhere to give them context.

In what format do people want forecast information?

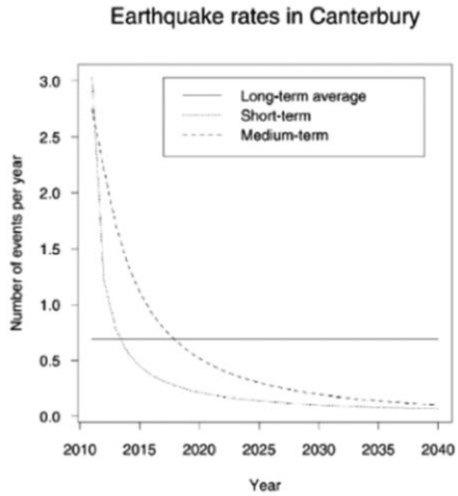
(Becker *et al.*, 2019) showed their participants various formats of OEF communication and asked their opinions. Seeing a table (right) with the forecasted number of shocks of a certain magnitude alongside the actual observed number was found to be reassuring of the accuracy of the forecast.

Dates	Expected numberof after shocks of magnitude 4.0-4.9	Observed	Expected numberof after shocks of magni-tude 5.0 and above	Observed
Sep 4	43 - 73	33	2 - 12	6
Sep 5	11 - 29	18	0 - 5	1
Sep 6 - Sep 12	28 - 53	35	1 - 9	4
Sep 13 - Sep 19	8 - 23	20	0 - 5	0
Sep 20 - Sep 26	4 - 16	8	0 - 3	0
Sep 27 - Oct 3	2 - 13	3	0 - 3	0
Oct 4 - Oct 31	10 - 26	15	0 - 4	3
Nov 1 - Nov 28	5 - 17	11	0 - 4	0
Nov 29 - Dec 26	3 - 13	4	0 - 3	0
Dec 27 - Jan 23	2 - 11	8	0 - 3	1
Jan 24 - Feb 20	1 - 9	5	0 - 2	0
Feb 21 - Feb 22	0 - 2	0	0 - 1	0
M6.3 sequence commences				
Feb 22 - Feb 28	12 - 29	56	0 - 5	4
Mar 1 - Mar 7	1 - 10	5	0 - 2	0
Mar 8 - Mar 14	0 - 6	8	0 - 2	0
Mar 15 - Mar 21	2 - 11	0	0 - 2	1

Map presentations (below) were thought less useful. Although participants liked the gradients of colour as they conveyed the continuous nature of the changing risk and thought the colour choice intuitive, the expert audience questioned whether 'red' and 'green' might be misinterpreted as 'danger' and 'safe'. The public audience found that the maps did not help their decision-making and the 24-hour period of the forecast was thought too short, with the probabilities too low, to be useful.



A graph format (below), designed with structural engineers in mind, was thought useful at showing the decline of projected frequency of earthquakes, although some wondered whether the public might find it showed a lessening case for preparation.



Finally, a table designed to show forecast probabilities for a technical audience (below) was deemed difficult to understand by many participants, but useful by certain specialists, who appreciated the uncertainty ranges and who commented that careful choice of the magnitude ranges displayed would be needed.

Start Date		+1 Year			+1 Month			+7 Days		
	Mag Range	Avg. expectation	Poisson conf. bounds	Prob.	Avg. expectation	Poisson conf. bounds	Prob	Avg. expectation	Poisson Conf. bounds	Prob
15/6/11	5.0-5.9	4.1	[1 8]	98%	1.85	[0 5]	84%	1.0	[0 3]	63%
	6.0-7.9	0.42	[0 2]	34%	0.7	[0 1]	16%	0.09	[0 1]	9%
15/7/11	5.0-5.9	2.5	[0 6]	92%	0.45	[0 2]	36%	0.14	[0 1]	13%
	6.0-7.9	0.3	[0 2]	26%	0.05	[0 1]	5%	0.01	[0 1]	1%
15/8/11	5.0-5.9	2.2	[0 5]	89%	0.34	[0 2]	29%	0.09	[0 1]	9%
	6.0-7.9	0.2	[0 1]	18%	0.04	[0 1]	4%	0.009	[0 1]	<1%

As shown in our other case study, USGS communicate operational aftershock forecasts (OAFs) using an automated template that is integrated into the USGS recent earthquake event webpages, allowing for more rapid dissemination of OAFs than previous systems where reports were produced ad hoc with no automation (Michael *et al.*, 2019). These templates are in a tiered format that provides basic information up top, then goes on to provide more detailed numerical information (McBride *et al.*, 2018; Michael *et al.*, 2019). During the Anchorage earthquake sequence that followed the 2018 M7.1 earthquake, it was found that these forecasts were mostly reported accurately by the media except in a few cases where the probability of one or more events in a given time-magnitude window was merged incorrectly with the likely range in the number of aftershock events. The template of these OAF communications has since been updated to reduce such confusion going forward (Michael *et al.*, 2019).

The challenge of small probabilities

One significant concern about OEF is that communicating the small probabilities inherent to its short term forecast nature might undermine people's willingness to act compared to if only the larger probabilities associated with long-term hazard forecasts were communicated (Wang and Rogers, 2014). Indeed communicating probabilistic information in a way which is comprehensible for expert users and which motivates them to take preparedness actions is difficult (Wein *et al.*, 2016; Roeloffs and Goltz, 2017; Becker *et al.*, 2019, 2020). However, there is empirical evidence from (Doyle *et al.*, 2018, 2020) that during the 2013 Cook Strait earthquake sequence in New Zealand, people's perceptions of likelihood information presented in aftershock forecasts was positively related to preparedness actions (although it should be noted that the probabilities being communicated during an aftershock sequence are typically substantially larger than would be the case in "regular" OEF communications).

Communicating time windows over which events can occur (such as "there is a 1% chance of a magnitude M7 earthquake in the next month") is commonplace in the communication of operational earthquake forecasts and aftershock forecasts. There is evidence that people show skew in perception of likelihoods of earthquakes occurring towards the end of the time period communicated, discounting the risk posed today, which could delay decisions such as issuing alerts or evacuation for example (McClure, Doyle and Velluppillai, 2015; Doyle *et al.*, 2020). Evidence from studies of communications of probabilities over longer time frames for likelihoods of volcanic eruptions (Doyle *et al.*, 2011; Doyle, McClure, Johnston, *et al.*, 2014) has shown that this skew can be somewhat mitigated by communicating probabilities of these events as occurring *within* a certain number of years, rather than *in* a certain number of years. However when one volcanology study went on to test this effect for shorter time windows, more relevant to operational earthquake forecasts and aftershock forecast communications and the decisions that emergency services might have to make during an aftershock sequence, they showed that use of the word 'within' did not negate the skew in this case (Doyle, McClure, Johnston, *et al.*, 2014). Nevertheless, the approach has been adopted by both GNS Science and USGS in their OEF and aftershock communications, as can be seen in both our earlier case studies.

Searching for a psychological explanation, (Doyle, McClure, Johnston, *et al.*, 2014) suggest that the upwards skew towards the end of a forecast window may be attributable to people overlaying the provided statement with their own mental models of the hazard event in question (e.g. (Wood *et al.*, 2012; Bostrom *et al.*, 2016)), and that these mental models may in some instances consist of erroneous beliefs about how an event's likelihood changes through time (Whitney, Lindell and Nguyen, 2004). They liken this to a base-rate effect, where an individual's prior belief about the frequency of an event (itself influenced by contextual factors) is combined with the probability they are presented with to produce an interpretation of that probability (Windschitl and Weber, 1999; McClure, Doyle and Velluppillai, 2015). They also note a possible role for optimism bias (Sharot, 2011) and temporal discounting (Milfont, Wilson and Diniz, 2012) to explain lower perceived likelihoods in the nearer term.

As a practical outcome, (Doyle, McClure, Paton, *et al.*, 2014) went on to recommend that to try and reduce these biased interpretations across forecast windows, they should be communicated over a variety of time frames, particularly in the very short term (the first 24 hours). They argue that this immediate time window would act as an anchor to centre the information on the present and thus reduce underestimations of likelihood at the beginning of forecast windows. Doyle et al. (2020) in fact had the opportunity to test the efficacy of their advice in reducing the skew in perceived likelihood of earthquake aftershock forecasts given over a short time window (24 hours to one week) and future, OEF forecasts given over a longer time window (7 days to 1 year), in a well-timed survey run after the 2013 Cook Strait earthquake sequence in New Zealand.

The short time window statement communicated weekly forecast probabilities, and contained a 24 hour forecast window as the anchoring time statement. The longer-term forecast communicated yearly forecast probabilities, with a 7 day forecast window included as the anchoring statement. They found that the short term forecast - complete with anchoring window - did not show the skew that a similar forecast in previous work by (McClure, Doyle and Velluppillai, 2015) had done, however there was still skew in interpretations of the longer term forecast. They speculate that the long time window in this longer term forecast may encourage greater temporal distancing of likelihoods than the short 24 hour to one week forecast, thus reducing the effectiveness of an anchoring time statement in mitigating these effects. The results of this research are encouraging, at least for presentations of short term, aftershock probabilities, although as (Doyle *et al.*, 2020) themselves note, further experimental research examining for skew effects in interpretations of forecasts with and without short term anchoring statements will be necessary to conclude more definitively the efficacy of the anchoring time statement approach.

The problem with communicating probabilities is not limited simply to very small numbers. (Becker *et al.*, 2020) investigated people's understanding of the probability of an earthquake in the Wellington region of New Zealand in 2016. Whilst the forecast probability for a MMI 7+ earthquake in the next 12 months was 5% at the time, participants' estimates ranged between 0-90%, with only a quarter of people selecting 5% or less. Although it is not surprising that people's numerical estimations were wildly off, and this does not necessarily indicate that their perceptions of the risk were wrong, only their translation of their subjective perception to a numerical label, (Becker *et al.*, 2020) recognised a confusion over time periods and how that related to probabilities.

The challenge of loss of trust and 'false alarms'

As previously noted in the case of tornado warnings, evidence for whether or not 'false alarms' have a negative effect on trust is not yet conclusive, however rapid communication of the reasons behind a forecast or alert is likely to lower the potential for reputational and trust damage.

Shakealert is the USGS Earthquake Early Warning system for the West Coast of the USA that is currently transitioning into public messaging. McBride et al. (2020) explored the value and efficacy of post-alert messaging as an addition to the current system. Such messages are sent after the early warning alert and serve as an evaluation of the performance of the alert that can update emergency managers and technical operators of the alert system of the alert's reliability, and manage the expectations and inform the response of public audiences to future alerts (McBride, 2020).

(Becker *et al.*, 2020) encountered problems with credibility and trust in New Zealand, with participants in their surveys reporting *"When you publish probabilities for aftershocks of two significant figures, such as 98%, you lose all credibility with me. There is no way that you can predict with such supposed accuracy."* and emphasise the need to communicate ranges rather than point estimates to reinforce the uncertainty, particularly at higher probabilities (which imply greater certainty).

The role of emotions and previous experience

Although not of direct practical relevance, there has been some research on the role of emotions and experience on the interpretations of OEF. As might be expected, levels of concern about both immediate aftershocks and longer-term future earthquakes is an important influence on people's decisions to take preparedness actions (Becker *et al.*, 2017; Doyle *et al.*, 2018), as too are emotions during and in the immediate aftermath of an earthquake (not just those about anticipated future events) (Goltz, Russell and Bourque, 1992).

Only recently, however, has there been research into the effects of emotions on interpretations of earthquake forecasts directly. (Becker *et al.*, 2019) demonstrated a role for emotion in interpretations of probabilistic statements in aftershock forecasts issued during the Canterbury Earthquake sequence in New Zealand. (Doyle *et al.*, 2018) examined the influence of emotions on perceptions of aftershock forecasts issued during the 2013 Cook Strait earthquake sequence in New Zealand, as well as on a longer term operational earthquake forecast for Wellington. For aftershock forecasts, they demonstrated that ratings of how concerned participants felt about the forecast were not correlated with their perceptions of the likelihoods. However, their concern about immediate aftershocks themselves (rather than the forecast information) *was* correlated, with those people who were more concerned about immediate aftershocks perceiving the forecast likelihoods to be higher than those who were less concerned. They also showed that participants' ratings of anxiety about the forecast, as well as their feelings of fear, nervousness and alertness regarding the experience of the main Cook Strait earthquake itself was correlated with perceptions of likelihood (again higher ratings for each of these were related to higher perceived likelihoods). Although perhaps counterintuitively, there was a similar relationship between higher ratings of relief about the aftershock statement and higher likelihood ratings. Notably, there was no relationship between participant's levels of concern about the future earthquakes in the longer term and the perceived likelihood of these future earthquakes, supporting the idea that emotions are more important for shorter term risk perceptions and resultant perceived likelihoods of earthquakes than they are for longer term perceptions (Dooley *et al.*, 1992; Pennebaker and Harber, 1993).

Both (Doyle *et al.*, 2020) and (Becker *et al.*, 2019) also demonstrate an important role for past experience on perceptions of earthquake forecasts (not just the emotions associated with these experiences). (Doyle *et al.*, 2020) demonstrated that those that experience more shaking during the main Cook Strait earthquake perceived significantly higher likelihoods when viewing aftershock forecasts. In their study of information needs and perceptions of aftershock forecasts during the Canterbury earthquake sequence, (Becker *et al.*, 2019) also demonstrated a role for past experience in interpretations of probabilistic forecasts. They went on to show that information needs and perceptions of likelihood evolved through sequence depending on the impacts people experienced and the role they played in the event. People drew on things like the shaking they felt or the noises they heard, in combination with reported earthquake information, to make assessments about the impact of an earthquake and location of future events in the sequence, as well as to inform the actions they took. These types of experiences can be characterised as “environmental cues”, as described in the Protective Action Decision Model (PADM) of Lindell & Perry (2012).

Other effects on interpretation of OEFs are worldviews and social norms (Doyle, McClure, Paton, *et al.*, 2014; Wein *et al.*, 2016; Becker *et al.*, 2019), people’s prior knowledge about earthquakes, the extent to which knowledge is personalised and contextualised, and credibility and trust (Becker *et al.*, 2019). One possible practical approach described by (Becker *et al.*, 2019) is for scientists to be prepared to share their personal experiences and emotions and help establish the social norms. They describe a ‘magnitude guessing game’ where after every aftershock people would socially try to guess the magnitude and then use the GeoNet website to confirm it and see who was closest. It helped people get a feeling for the scale and tie the forecasts in with their personal experiences.

10.2.7. Impact based forecasting

Across many of the fields we’ve discussed, the need for information on impacts of forecasted events has been highlighted. People don’t just need to know that an event is likely to occur, they need to know what the potential impacts of that event will be, and in turn what they should do in response to this. As we’ve discussed, a risk is not just the hazard itself, but the combination of that hazard with the amount of things (people, buildings, agriculture) exposed, and the vulnerability of those things to the hazard they are exposed to. To illustrate this, consider the earthquake doublet that hit south-west Iceland, close to the capital of Reykjavik, on 17th and 21st June 2000 respectively. The first of the main events was registered as magnitude Mw6.5, and the second Mw6.4 (Stefánsson, Guðmundsson and Halldórsson, 2000). There were no fatalities, although 793 buildings experienced some damage and 30 were replaced having suffered extreme damage (Bessason *et al.*, 2012; Ioannou *et al.*, 2018). Consider now the mainshock of the L’Aquila earthquake sequence in Italy, of 6th April 2009, which was registered as magnitude Mw6.3 (Alexander, 2010). This main shock killed 308 people, injured 1500 (of whom 202 were seriously injured) and caused serious damage to 60,000 buildings (Casarotti, Pavese and Peloso, 2009; Volpini, 2009; Alexander, 2010). Two earthquakes of similar magnitude in two different locations, with two drastically different outcomes. Hazard-only information would imply the events were very similar, but as soon as you consider the impacts, they appear very different indeed.

Typically, communications of forecasts about hazards have been hazard- or "phenomenon-" specific, for example what the likelihood of a particular earthquake of a particular magnitude will be for a certain area, or what the wind speed will be for an incoming hurricane for another. There is increasing emphasis however, on the importance of impact-based forecasting; forecasts that shift from talking about the likelihood of what a hazard will be like, and towards the likelihood of what a hazard will *do* (Red Cross Red Crescent and UK Met Office, 2018). It is hoped that this will not only improve the understanding and preparedness of agencies and the public (and their willingness to take appropriate action to issued warnings), but will also improve the efficacy of disaster response, and reduce its costs.

'Crucial evidence has been gathered to showcase the cost-effectiveness of early actions (triggered by impact-based forecasts). Across four case-studies, Return-of-Investment ratios ranged from USD 2.5-7.2 for every USD 1 spent on early interventions.' Food and Agriculture Organization. Global Dialogue Platform on FbF-Berlin 2018 , (German Red Cross, 2018)(Red Cross Red Crescent and UK Met Office, 2018)

Hazard	Forecast	Impact-based forecast for Individuals/ members of public	Impact based forecast for Sector specific users
Flooding	Heavy rain is forecast. 100 to 150mm of rain is expected within a three-hour period.	Flash flooding of the County River is expected. Dwellings, farm buildings and grazing land within 30m of the river channel are expected to flood and be damaged.	The forecast water level in the recreational district is expected to cross the +0.85 alert threshold in 5 days and remain above for a further 3 days. An impact forecast of loss of household assets is over 25% and affected population over 40%.
Tropical Cyclone	A tropical cyclone category 3, windspeed of 125 km/h is expected in the next 48 hours.	A tropical cyclone category 3, windspeed of 125 km/h is expected to make landfall in 12 hours, in X and Y regions, likely to damage critical infrastructure such as bridges, blocking transport from region X to region Y.	A Tropical cyclone, lead time of 30 hours, with wind speed greater than 125 km/h, corresponding to an impact forecast of damage of 25% of housing.

Comparisons between traditional hazard-based forecasts, impact-based forecasts designed for the public, and impact-based forecasts co-designed with sector-specific users. From (Red Cross Red Crescent and UK Met Office, 2018).

It has been shown that people are more likely to both believe and act upon a warning if they are knowledgeable about its impacts (Perry and Lindell, 1990; Earl J. Baker, 1991; Morss and Hayden, 2010), although it is important to note that information not just about what the hazard's impacts will be, but also about what people can do may be key to an audience's response. (Potter *et al.*, 2018) examined the efficacy of impact-based severe weather warnings on people's risk perceptions and their intent to take protective action in an online survey of the New Zealand public. Whilst the impact-based forecast was related to higher levels of concern and threat, as well as understanding of the potential impacts, than the regular "phenomenon-based" forecast, this did not translate into greater intentions to act. (Potter *et al.*, 2018) recommend that "what to do" information is included in impact-based forecasts and warnings to bridge this attitude-behaviour gap.

Several fields are starting to move towards impact based forecasting, including seismology (e.g. (Iervolino *et al.*, 2015; Chioccarelli and Iervolino, 2016)), although there has been a particularly substantial focus in the meteorological community. The World Meteorological Organisation (WMO) suggests that many of the casualties and damages that result from hydrometeorological events can be attributed to the gap between forecasts and the understanding agencies and the public have of their potential impacts ((Potter *et al.*, 2018)(World Meteorological Organization, 2015)) and indeed evidence from both Hurricane Sandy and Hurricane Ike in the US highlighted that people do not understand well what the impacts of forecasted severe weather and storm surges will be (Morss and Hayden, 2010; David P. Rogers and Tsirkunov, 2013). Resultantly, the WMO have called for a shift from more traditional, hazard based forecasts and warnings to those that link to impacts (World Meteorological Organization, 2015; Potter *et al.*, 2018).

As ever, effective communication of these impact-based forecasts will be vital to their success, and key to this will be knowing the needs of users. We recommend the "Impact Based Forecasting Guide" by the (Red Cross Red Crescent and UK Met Office (2018) and print below their summary of what information should be communicated, based on questions from both public- and sector-specific users of these forecasts.

	Information users require	
Key questions	**Sector specific users**	**Individuals/members of public**
What is going to happen?	▸ Summary of the hazard ▸ May include a technical summary with detail of the weather/climate parameter, such as magnitude of the hazard, probability/likelihood of event ▸ What are the potential impacts	Summary of the hazard *impacts*, avoiding technical terms
When will it happen?	▸ When will impacts begin? ▸ When will impacts stop occurring? ▸ Timing and location	▸ When will impacts begin? ▸ When will impacts stop occurring? ▸ Timing and location
How bad will it be and where?	▸ Assessment of the risk ▸ May include risk matrices, risk maps/ intervention maps ▸ Where will impacts take place ▸ How severe will the impacts be?	Clear, jargon-free explanation of risk, focussed on impacts
What can I do to reduce impacts?	Organisations will have actions and/or response plans to implement on issuance of the impact-based warning	Advice and guidance on what actions can be taken to prepare

User related questions for impact-based forecasting and warning. From "Impact Based Forecasting Guide" by the Red Cross Red Crescent and UK Met Office (2018)

11. Conclusions

For those wanting to communicate forecasts of seismic events, then, there is a lot that can be learned from what is already known – from social science research, from those who communicate forecasts in other fields, and from those who have already attempted operational earthquake forecasting. Most of these have already been drawn together previously by other researchers, but here perhaps we can flesh them out with more actionable advice than usual, based on the conversations that we have had with experts and practitioners within other fields.

1) Ensure that your audiences are as familiar as possible with what you are going to communicate, how to interpret it, and how to act on it.

- Work with journalists and the media (e.g. the twice-yearly workshops run by the Storm Prediction Service in the US in which media professionals and forecasters meet) to ensure that you are providing the information they need and that they understand the communications and their limitations, so that they can accurately convey the information to the public. Ensure the media are ready to interpret the hazard into the risks for the public: what would the consequences of a seismic event actually be, locally? Regular meetings are important as they ensure that new journalists are trained up, and that everyone is familiar with the communications before any event becomes 'news'.

- Similarly, hold regular (e.g. annual) meetings with emergency responders, infrastructure managers, and others who would need to respond to a seismic event. As above, ensure that you are providing the information they need and that they understand the communications you are providing. You could consider running practice drills to ensure that in the event of heightened activity, they all know what actions they should take. It is important for forecasters to be aware of 'thresholds' that trigger different emergency responses so that the consequences of every action or sign that forecasters might take or detect are known by everyone (as learned by tornado forecasters in the US, where certain threshold probabilities can trigger school closures in some states etc).

- Produce regular (e.g. daily or weekly) forecast information, even in times where there is no change or no significant seismic activity. This ensures that the channels of communication are open, well-oiled, and that everyone in the chain of communication is familiar with 'normal' activity and is therefore more ready to respond to any significant changes (as learned by the UK's Environment Agency when communicating flood forecasts).

- Work with schools, businesses, communities and with the media/government to ensure that children and the public in medium or high hazard areas (or across a whole country) know what preparations to make in the case of a raised level of alert, and what to do in the event of an earthquake. When an earthquake occurs, everyone needs to know instantly what to do, without having to stop and think about it. This requires regular training from a young age. The evidence that those who had had school training in how to respond in a storm in the US all survived an event when it happened, whilst there were deaths amongst those who didn't, suggests how important this training can be.

2) Be aware of the psychology of 'risk': someone's perception of a risk is, quite rightly, influenced by far more than just the likelihood and severity of an event.

- Individuals' personal vulnerability (how the event would affect them personally if it happened, e.g. their financial situation, health status, the vulnerability of their house to damage), their previous experience with seismic events, and how much they feel they have responsibility and control over the outcome of an event are important parts of how they will react to information about a risk. Instead of trying to make people worry about an event happening, it is probably more helpful to aim for 'resilience' (as the UK flood resilience teams do). Ensure that people feel that there are concrete and achievable steps they can take, individually, to protect themselves, and to make reminders of the hazard and what actions to take a regular part of life (e.g. through making the seismic forecast a part of the weather forecast in medium to high hazard areas, alongside reminders of what to do in the event of an earthquake).

- Trust in the sources of information about the risk is very important. Try to avoid politicisation by working with a very broad range of organisations, including religious groups across the spectrum, all political groups, all media outlets, local community groups and social/charitable groups. People judge communicators on what their motivations seem to be, so ensure that there are no perceptions of conflicts of interest: it is entirely motivated by the desire to save lives and livelihoods, and that the actions that can be taken are individual as well as collective and societal.

3) Test all potential communications with their intended audiences to try to maximise their ease of comprehension (and minimise the chance of misunderstandings). There are a few particular areas that are worth considering:

- Work with others to help communicate the potential impacts of forecast events, not just the event itself. Learn from the experience of the winter storm forecasters in the US who warned that a storm was coming, but the public didn't anticipate what exact challenges, risks and impacts that weather would bring.

- Small numbers are very hard to understand. Ways to avoid tiny (and hence meaningless) absolute risks are to communicate relative risks, represent the numbers in a graphical way (e.g. through colours or points on a scale), use a larger time frame over which they are being considered, give the numbers context in the form of comparators (e.g. 'as likely as…' or 'similar to the event in 1956'). However, each of these will have a different effect on the audience so need to be empirically tested.

- Give people context to help them understand the risk, such as examples from the past with which to compare the predicted future (e.g. showing what the seismic activity has been over the past year, or during a period of seismic activity that would be familiar to them).

- Do not use verbal terms (e.g. 'likely', 'severe') without a cue as to the numerical likelihood or impact that they represent – different people will interpret words in different ways.

- Too much information at once makes it much more likely that the important message will be lost. Design your communications so that people get only the information they need to make their key decisions first, and then allow them to drill down to more detail if they want. For example, do they need information across a broad geographical area (in which case a map might be most helpful), or do they need information only about a small geographic area, but in more detail or over time (in which case a timeline might be most helpful). What level of event do they need to know about (any felt event, or only above a certain threshold of impact)?

- What time period do your different audiences want/need the forecast to cover? Over what time period does it become too uncertain/too little trusted to be of use?

- Graphics are very useful, and familiarity of a graphical format makes it much easier for people to understand 'at a glance'. Weather forecasts, using certain icons and terminology, have become embedded within culture (although some aspects, such as probabilistic information, are still widely misunderstood). Where possible use formats or icons that are culturally familiar, but always have a text explanation available. Where a new format promises better comprehension through empirical testing, don't be afraid to introduce it, but ensure that the audience are exposed to it (with explanation) regularly and during seismically quiet times, to allow them to become familiar with the format and how to interpret it.

- Remember however, that not all commonly used graphical techniques are necessarily examples of best practice. For example, according to cartographic principles, circles of different sizes are considered a good way of conveying different quantities on a map as it is thought that this gradation in size tunes into an intuitive perception that bigger symbols represent higher (larger, stronger etc) values. On this basis, such an approach is widely used in map design. However evidence suggests that perceptual biases mean that people find it very hard to accurately assess areas and volumes (Lipkus and Hollands, 1999). This means that representing variation in quantities using area of circles is not likely to lead to accurate perceptions.

- Be very careful in the use of colours. Although 'red/green' may be a common way to indicate levels of danger, it can not only produce misperceptions (that 'green' is 'safe') but also is difficult for those with different forms of colour blindness. Colour gradient scales should also be chosen carefully to avoid artifacts of perception that seem to create banding rather than indicating a smooth gradient.

- Ensure that behavioural advice is given alongside the forecast, telling people what action they should take as a result of the forecast (reminding them that a high-impact event can occur at any time), as the UK Met Office has learned is helpful for their forecasts.

- One communication method rarely suits all. Expert audiences and lay audiences interpret things differently; emergency responders and the public have different information needs; people with different experiences of the hazard are likely to respond differently. Be prepared to have several different types of communication, and where possible to allow people to choose which they want (e.g. different presentations on a website or app).

- Give quantified uncertainties in the form of a range (or represent the range graphically – what format you use will need testing), but also be careful to warn people of the unquantifiable uncertainties and that seismic events are inherently unpredictable. Although weather forecasters have been wary of using probabilistic forecasts, and they can be misunderstood, there is evidence that a public audience make better decisions when armed with probabilities than deterministic forecasts (although using low absolute probabilities may be tricky). Here training and working with the media to help them phrase the probabilities and give regular translations of what they mean in lay language in their communications may help.

- Be as transparent as possible about the information available to you. You might consider following the UK Environment Agency's lead in allowing public access to the readings on individual sensors via their website, so that they can see the raw data and the sensors most local to them.

- Consider communicating information about likely timings. Although it is not possible to forecast when a seismic event may occur, it may be useful for audiences to know how long seismic events usually last, and how long they should wait after an event before leaving a place of safety (as was found by the US tornado forecasters), or starting emergency support etc. (as was found by USGS in their trials of operational earthquake forecasting).

- Expect to have to provide a personal interpretation service for those who are concerned and want to check with a 'real person' how to interpret the forecast (particularly in times of heightened seismic activity). If this is outsourced to a media or communications centre they need to have the expertise to do the interpretation accurately.

- Consider 'prebunking' common misinformation/misunderstandings.

4) Don't confuse 'everyday' forecast communications with warnings. The two have different aims (forecasts are providing regular information, warnings are there to trigger behaviour) and hence use very different communications strategies.

This review has been specifically about forecast information, and whilst it occasionally touches on warnings and ensuring that forecasts are understandable and actionable when they are providing a warning, this is different from providing emergency information (e.g. Earthquake Early Warning), so this review should not be considered a reference for those designing emergency and warning messages.

12. Acknowledgements

This work was funded by the Horizon 2020 project RISE. We would like to thank all our anonymous interviewees for their time and insights. We would also like to thank our colleagues at GNS Science and USGS, and our RISE collaborators, particularly Michèle Marti, Warner Marzocchi, Rémy Bossu and Danijel Schorlemmer. Finally, thank you to Alice Lawrence of the Winton Centre for Risk and Evidence Communication for her assistance in designing interview schedules, and in conducting and analysing interviews.

13. References

Abraham, S. *et al.* (2015) 'Do location-specific forecasts pose a new challenge for communicating uncertainty?', *Meteorological Applications*, 22(3), pp. 554–562. doi: 10.1002/met.1487.

Adams, R. M. *et al.* (2017) 'Who participates in the great shakeout? Why audience segmentation is the future of disaster preparedness campaigns', *International Journal of Environmental Research and Public Health*, 14(11), pp. 1–13. doi: 10.3390/ijerph14111407.

Alexander, D. E. (2010) 'The l'Aquila earthquake of 6 April 2009 and Italian government policy on disaster response', *Journal of Natural Resources Policy Research*, 2(4), pp. 325–342. doi: 10.1080/19390459.2010.511450.

Allcott, H. and Gentzkow, M. (2017) 'Social Media and Fake News in the 2016 Election', *Journal of Economic Perspectives*, 31(2), pp. 211–236. doi: 10.1257/jep.31.2.211.

Allis, E. *et al.* (2019) *The Future of Climate Services*.

Appleby-Arnold, S. *et al.* (2019) 'Truth, trust, and civic duty: Cultural factors in citizens' perceptions of mobile phone apps and social media in disasters', *Journal of Contingencies and Crisis Management*, 27(4), pp. 293–305. doi: 10.1111/1468-5973.12282.

Armstrong, C. L., Cain, J. A. and Hou, J. (2020) 'Ready for disaster: information seeking, media influence, and disaster preparation for severe weather outbreaks', *Atlantic Journal of Communication*. Routledge, 00(00), pp. 1–15. doi: 10.1080/15456870.2020.1731512.

Baddeley, A. (1992) 'Working memory.', *Science*, 255(5044), pp. 556–559.

Bahk, C. and Neuwirth, K. (2000) 'Impact of Movie Depictions of Volcanic Disaster on Risk Perception and Judgements', *International journal of mass emergencies and disasters*, 18, pp. 65–84.

Baker, E. *et al.* (2012) 'Risk Perceptions and Preparedness among Mid-Atlantic Coastal Residents in Advance of Hurricane Sandy', *Working Paper # 2012-18*, pp. 1–44. Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.420.8639&rep=rep1&type=pdf.

Balluz, L. *et al.* (2000) 'Predictors for people's response to a tornado warning: Arkansas, 1 March 1997', *Disasters*, 24(1), pp. 71–77. doi: 10.1111/1467-7717.00132.

Barnett, J. and Breakwell, G. M. (2003) 'The Social Amplification of Risk and the Hazard Sequence: The October 1995 OC Pill Scare', *Health, Risk & Society*, 5(3), pp. 301–13.

Barnston, A. G., He, Y. and Unger, D. A. (2000) 'A forecast product that maximizes utility for state-of-the-art seasonal climate prediction', *Bulletin of the American Meteorological Society*, 81(6), pp. 1271–1279. doi: 10.1175/1520-0477(2000)081<1271:AFPTMU>2.3.CO;2.

Barthel, M., Mitchell, A. and Holcomb, J. (2018) 'Pew Research Center: Many Americans believe fake news is sowing confusion', pp. 1–15. Available at: https://www.journalism.org/2016/12/15/many-americans-believe-fake-news-is-sowing-confusion/.

Basol, M., Roozenbeek, J. and van der Linden, S. (2020) 'Good News about Bad News: Gamified Inoculation Boosts Confidence and Cognitive Immunity Against Fake News', *Journal of Cognition*, 3(1)(2), pp. 1–9. doi: https://doi.org/10.5334/joc.91.

BBC News (2016) *New Zealand quake: Preacher under fire over homosexuals claim*, *BBC News*. Available at: https://www.bbc.co.uk/news/world-asia-38011627 (Accessed: 16 November 2020).

BBC News (2020) 'Ofcom: Covid-19 5G theories are "most common" misinformation', *www.bbc.co.uk*, April.

Bean, H. *et al.* (2015) 'The study of mobile public warning messages: A research review and agenda', *Review of Communication*. Taylor & Francis, 15(1), pp. 60–80. doi: 10.1080/15358593.2015.1014402.

Becker, J. S. *et al.* (2010) *Perceptions of flooding in four Australian communities : results of focus groups with residents Lower Hutt, N.Z.*

Becker, J. S. *et al.* (2013) 'Salient beliefs about earthquake hazards and household preparedness', *Risk Analysis*, 33(9), pp. 1710–1727. doi: 10.1111/risa.12014.

Becker, J. S. *et al.* (2015) 'A review of people's behavior in and around floodwater', *Weather, Climate, and Society*, 7(4), pp. 321–332. doi: 10.1175/WCAS-D-14-00030.1.

Becker, J. S. *et al.* (2016) 'Evaluating New Zealand's "ShakeOut" national earthquake drills: a comparative analysis of the 2012 and 2015 events', *Proceedings of the 2016 NZSEE Conference, Christchurch, New Zealand*, pp. 1–3.

Becker, J. S. *et al.* (2017) 'The role of prior experience in informing and motivating earthquake preparedness', *International Journal of Disaster Risk Reduction*. Elsevier Ltd, 22(March), pp. 179–193. doi: 10.1016/j.ijdrr.2017.03.006.

Becker, J. S. *et al.* (2019) 'When the earth doesn't stop shaking: How experiences over time influenced information needs, communication, and interpretation of aftershock information during the Canterbury Earthquake Sequence, New Zealand', *International Journal of Disaster Risk Reduction*. Elsevier Ltd, 34(November 2018), pp. 397–411. doi: 10.1016/j.ijdrr.2018.12.009.

Becker, J. S. *et al.* (2020) 'Forecasting for a Fractured Land: A Case Study of the Communication and Use of Aftershock Forecasts from the 2016 Mw 7.8 Kaikōura Earthquake in Aotearoa New Zealand', *Seismological Research Letters*, (November). doi: 10.1785/0220190354.

Bekker, H. L. *et al.* (2013) 'Do personal stories make patient decision aids more effective? A critical review of theory and evidence.', *BMC medical informatics and decision making*, 13 Suppl 2(Suppl 2), p. S9. doi: 10.1186/1472-6947-13-S2-S9.

Bell, H. M. and Tobin, G. A. (2007) 'Efficient and effective? The 100-year flood in the communication and perception of flood risk', *Environmental Hazards*, 7(4), pp. 302–311. doi: 10.1016/j.envhaz.2007.08.004.

Ben-Tal, O., Daniels, M. and Berger, J. (2001) 'De Natura Sonoris: Sonification of Complex Data', *Mathematics and Simulation with Biological, Economical and Musioacoustical Applications Mathematics and Computers in Science and Engineering*, p. 330.

Bertin, J. (1983) *Semiology of graphics: Diagrams networks maps*. Madison, WI, WI: University of Wisconsin Press.

Bessason, B. *et al.* (2012) 'Probabilistic Earthquake Damage Curves for Low-Rise Buildings Based on Field Data', *Earthquake Spectra*, 28(4), pp. 1353–1378. doi: 10.1193/1.4000082.

Blakley, J., Chen, N. and Kaplan, M. (2009) *An Evaluation of the First Great Southern California ShakeOut*. Available at: http://earthquake.usgs.gov/regional/nca/simulations/shakeout/.

van der Bles, A. M. *et al.* (2019) 'Communicating uncertainty about facts, numbers and science', *Royal Society Open Science*, 6(5). doi: 10.1098/rsos.181870.

van der Bles, A. M. *et al.* (2020) 'The effects of communicating uncertainty on public trust in facts and numbers'.

Van Der Bles, A. M. *et al.* (2019) *Determining and facilitating the clearest ways to visualize uncertainty around estimates , time series and curves*.

Bonner, C. and Newell, B. R. (2008) 'How to make a risk seem riskier: The ratio bias versus construal level theory.', *Judgment and Decision Making*. Newell, Ben R.: School of Psychology, University of New South Wales, NSW, Australia, 2052, ben.newell@unsw.edu.au, Ben R.: School of Psychology, University of New South Wales, NSW, Australia, 2052, ben.newell@unsw.edu.au: Society for Judgment and Decision Making, pp. 411–416.

Borkin, M. A. *et al.* (2013) 'What makes a visualization memorable', *IEEE Transactions on Visualization and Computer Graphics*. IEEE, 19(12), pp. 2306–2315. doi: 10.1109/TVCG.2013.234.

Borkin, M. A. *et al.* (2016) 'Beyond Memorability: Visualization Recognition and Recall', *IEEE Transactions on Visualization and Computer Graphics*. IEEE, 22(1), pp. 519–528. doi: 10.1109/TVCG.2015.2467732.

Bostrom, A. *et al.* (2016) 'A mental models study of hurricane forecast and warning production, communication, and decision-making', *Weather, Climate, and Society*, 8(2), pp. 111–129. doi: 10.1175/WCAS-D-15-0033.1.

Bostrom, A., Anselin, L. and Farris, J. (2008) 'Visualizing seismic risk and uncertainty: A review of related research', *Annals of the New York Academy of Sciences*, 1128, pp. 29–40. doi: 10.1196/annals.1399.005.

Brath, R. and Peters, M. (2004) 'Dashboard design: Why design is important', *DM Review*, October.

Brilly, M. and Polic, M. (2005) *Public perception of flood risks, flood forecasting and mitigation*, *Natural Hazards and Earth System Science, Copernicus Publications on behalf of the European Geosciences Union*. doi: 10.5194/nhess-5-345-2005.

Britton, E., Fisher, P. and Whitley, J. (1998) *The Inflation Report projections: understanding the fan chart*, *Bank of England. Quarterly Bulletin*.

De Bruin, W. B. *et al.* (2000) 'Verbal and Numerical Expressions of Probability: "It's a Fifty-Fifty Chance"', *Organizational Behavior and Human Decision Processes*, 81(1), pp. 115–131. doi: 10.1006/obhd.1999.2868.

Budescu, D. V. *et al.* (2014) 'The interpretation of IPCC probabilistic statements around the world', *Nature Climate Change*, 4(6), pp. 508–512. doi: 10.1038/nclimate2194.

Budescu, D. V., Broomell, S. B. and Por, H.-H. (2009) 'Improving communication of uncertainty in the reports of the Intergovernmental Panel on Climate Change', *Psychological Science*, 20(3), pp. 299–308. doi: 10.1111/j.1467-9280.2009.02284.x.

Budescu, D. V., Por, H.-H. and Broomell, S. B. (2012) 'Effective communication of uncertainty in the IPCC reports', *Climatic Change*, 113(2), pp. 181–200. doi: 10.1007/s10584-011-0330-3.

Camerer, C. F. and Kunreuther, H. (1989) 'Decision Processes for Low Probability Events: Policy Implications', *Journal of Policy Analysis and Management*, 8(4), pp. 565–592. doi: 10.3109/15569527.2012.667030.

Cameron, K. . *et al.* (2013) 'Patient Knowledge and Recall of Health Information Following Exposure to "Facts and Myths" Message Format Variations', *Patient Education and Counseling*, 92(3), pp. 381–387. doi: 10.1016/j.pec.2013.06.017.Patient.

Carroll, J. M., Mack, R. L. and Kellogg, W. A. (1988) *Interface Metaphors and User Interface Design*, *Handbook of Human-Computer Interaction*. Elsevier B.V. doi: 10.1016/b978-0-444-70536-5.50008-7.

Cartwright, W. (1997) 'New media and their application to the production of map products', *Computers and Geosciences*, 23(4), pp. 447–456. doi: 10.1016/S0098-3004(97)00008-3.

Casarotti, C., Pavese, A. and Peloso, S. (2009) 'Seismic Response of the San Salvatore Hospital of Coppito (L'Aquila) During the 6th April 2009 Earthquake', *Progettazione sismica*, 1(January), pp. 159–172.

Cauvin, C., Escobar, F. and Serradji, A. (2010) *Cartography and the Impact of the Quantitative Revolution*. London: Wiley-ISTE.

Chan, M. pui S. *et al.* (2017) 'Debunking: A Meta-Analysis of the Psychological Efficacy of Messages Countering Misinformation', *Psychological Science*, 28(11), pp. 1531–1546. doi: 10.1177/0956797617714579.

Chaney, P. L. *et al.* (2013) 'Household preparedness for Tornado hazards: The 2011 disaster in DeKalb County, Alabama', *Weather, Climate, and Society*, 5(4), pp. 345–358. doi: 10.1175/WCAS-D-

12-00046.1.

Chang, C.-T. (2007) 'Interactive Effects of Message Framing, Product Perceived Risk, and Mood{\textemdash}The Case of Travel Healthcare Product Advertising', *Journal of Advertising Research*. Journal of Advertising Research, 47(1), pp. 51–65. doi: 10.2501/S0021849907070067.

Chewning, E. G. and Harrell, A. M. (1990) 'The effect of information load on decision makers' cue utilization levels and decision quality in a financial distress decision task', *Accounting, Organizations and Society*, 15(6), pp. 527–542. doi: 10.1016/0361-3682(90)90033-Q.

Chioccarelli, E. and Iervolino, I. (2016) 'Operational earthquake loss forecasting: a retrospective analysis of some recent Italian seismic sequences', *Bulletin of Earthquake Engineering*, 14(9), pp. 2607–2626. doi: 10.1007/s10518-015-9837-8.

Le Clerc, J. and Joslyn, S. (2012) 'Odds ratio forecasts increase precautionary action for extreme weather events', *Weather, Climate, and Society*, 4(4), pp. 263–270. doi: 10.1175/WCAS-D-12-00013.1.

Cohen, D. J., Ferrell, J. M. and Johnson, N. (2002) 'What very small numbers mean', *Journal of Experimental Psychology: General*, 131(3), pp. 424–442. doi: 10.1037/0096-3445.131.3.424.

Coles, A. R. and Hirschboeck, K. K. (2020) 'Driving into danger: Perception and communication of flash-flood risk', *Weather, Climate, and Society*, 12(3), pp. 387–404. doi: 10.1175/WCAS-D-19-0082.1.

Compton, J. (2013) 'Inoculation theory', in Publications, S. (ed.) *The SAGE handbook of persuasion: Developments in theory and practice*. 2nd edn. Thousand Oaks, pp. 220–236.

Compton, J., Jackson, B. and Dimmock, J. A. (2016) 'Persuading others to avoid persuasion: Inoculation theory and resistant health attitudes', *Frontiers in Psychology*, 7(February), pp. 1–9. doi: 10.3389/fpsyg.2016.00122.

Cook, J., Ecker, U. and Lewandowsky, S. (2015) 'Misinformation and How to Correct It', in Scott, R. A. and Kosslyn, S. M. (eds) *Emerging Trends in the Social and Behavioral Sciences*. John Wiley & Sons, Inc, pp. 1–17. doi: 10.1002/9781118900772.etrds0222.

Cook, J., Lewandowsky, S. and Ecker, U. K. H. (2017a) 'Neutralizing misinformation through inoculation: Exposing misleading argumentation techniques reduces their influence', *PLOS ONE*. Public Library of Science, 12(5), pp. 1–21. doi: 10.1371/journal.pone.0175799.

Cook, J., Lewandowsky, S. and Ecker, U. K. H. (2017b) 'Neutralizing misinformation through inoculation: Exposing misleading argumentation techniques reduces their influence', *PLOS ONE*. Public Library of Science, 12(5), pp. 1–21. doi: 10.1371/journal.pone.0175799.

Correll, M. and Gleicher, M. (2014) 'Error Bars Considered Harmful: Exploring Alternate Encodings for Mean and Error', *IEEE Transactions on Visualization and Computer Graphics*, 20(12), pp. 2142–2151. doi: 10.1109/TVCG.2014.2346298.

Cosmides, L. and Tooby, J. (1996) 'Are humans good intuitive statisticians after all? Rethinking some conclusions from the literature on judgment under uncertainty', *Cognition*, 58(1), pp. 1–73. doi: 10.1016/0010-0277(95)00664-8.

Covello, V. T. (1991) 'Risk comparisons and risk communication: Issues and problems in comparing health and environmental risks', in Kasperson, R. E. and Stallen, P. J. M. (eds) *Communicating Risks to the Public: International Perspectives*. Dordrecht: Springer Netherlands, pp. 79–124. doi: 10.1007/978-94-009-1952-5_6.

Covello, V. T. (2003) 'Best practices in public health risk and crisis communication', *Journal of Health Communication*, 8, pp. 5–8. doi: 10.1080/713851971.

Covello, V. T., Sandman, P. M. and Slovic, P. (1988) *Risk Communication, Risk Statistics, and Risk Comparisons: A Manual for Plant Managers*. Washington, D.C.: Chemical Manufacturers Association.

Covello, V. T., von winterfeldt, D. and Slovic, P. (1986) 'Risk communication: A review of the literature', *Risk Abstract*, 3(4), pp. 171–182.

Crameri, F., Shephard, G. E. and Heron, P. J. (2020) 'The misuse of colour in science communication', *Nature Communications*. Springer US, 11(1), pp. 1–10. doi: 10.1038/s41467-020-19160-7.

Cresci, S. *et al.* (2015) 'Crisis mapping during natural disasters via text analysis of social media messages', in *Web Information Systems Engineering - WISE 2015*. doi: 10.1007/978-3-319-26187-4.

Creutin, J. . *et al.* (2009) 'Catchment dynamics and social response during flash floods: the potential of radar rainfall monitoring for warning procedures', *Meteorological Applications*, 16, pp. 115–125. doi: 10.1002/met.

Cunniffe, N. J. *et al.* (2015) 'Optimising and Communicating Options for the Control of Invasive Plant Disease When There Is Epidemiological Uncertainty', *PLoS Computational Biology*, 11(4), pp. 1–24. doi: 10.1371/journal.pcbi.1004211.

Cybulski, P. and Medyńska-Gulij, B. (2018) 'Cartographic redundancy in reducing change blindness in detecting extreme values in spatio-temporal maps', *ISPRS International Journal of Geo-Information*, 7(1). doi: 10.3390/ijgi7010008.

Damasio, A. (1994) *Descartes' error: emotion, reason, and the human brain.* New York: Grosset/Putnam.

Dash, N. and Gladwin, H. (2007) 'Evacuation Decision Making and Behavioral Responses: Individual and Household', *Natural Hazards Review*, 8(3), pp. 69–77. doi: 10.1061/(asce)1527-6988(2007)8:3(69).

David P. Rogers and Tsirkunov, V. V. (2013) *Weather and Climate Resilience: Effective Preparedness through National Meteorological and Hydrological Services*, *Book*. Available at: http://dx.doi.org/10.1596/978-1-4648-0026-9.

Deconinck, W. *et al.* (2017) 'Atlas : A library for numerical weather prediction and climate modelling', *Computer Physics Communications*, 220, pp. 188–204. doi: 10.1016/j.cpc.2017.07.006.

Delva, W. *et al.* (2012) 'HIV treatment as prevention: Principles of good HIV epidemiology modelling for public health decision-making in all modes of prevention and evaluation', *PLoS Medicine*, 9(7). doi: 10.1371/journal.pmed.1001239.

Demuth, J. L. *et al.* (2013) 'Improving effectiveness of weather risk communication on the NWS point-and-click web page', *Weather and Forecasting*, 28(3), pp. 711–726. doi: 10.1175/WAF-D-12-00118.1.

Dent, B.D. (1999) *Cartography, Thematic Map Design*. 5th edn. Dubuque: William C. Brown Publishers.

Dent, B. D. (1999) *Cartography: Thematic map design*. 5th edn. Duboque, IA: Brown.

Dieckmann, N. F. *et al.* (2017) 'Seeing What You Want to See: How Imprecise Uncertainty Ranges Enhance Motivated Reasoning', *Risk Analysis*, 37(3), pp. 471–486. doi: 10.1111/risa.12639.

Dieckmann, N. F., Peters, E. and Gregory, R. (2015) 'At Home on the Range? Lay Interpretations of Numerical Uncertainty Ranges', *Risk Analysis*. Dieckmann, Nathan F., Oregon Health & Science University, 3455 SW US Veterans Hospital Road, Portland, OR, US, 97239: Wiley-Blackwell Publishing Ltd., 35(7), pp. 1281–1295. doi: 10.1111/risa.12358.

Dilling, L. and Lemos, M. C. (2011) 'Creating usable science: Opportunities and constraints for climate knowledge use and their implications for science policy', *Global Environmental Change*. Elsevier Ltd, 21(2), pp. 680–689. doi: 10.1016/j.gloenvcha.2010.11.006.

Dooley, D. *et al.* (1992) 'Earthquake preparedness: Predictors in a Community Survey', *Journal of Applied Social Psychology*, 85(557), pp. 40–42. doi: 10.1007/978-3-642-41714-6_50224.

Douglas, M. (1992) *Risk and Blame: Essays in Cultural Theory*. London: Routledge.

Douglas, M. and Wildavsky, A. (1983) *Risk and culture: An essay on the selection of technological and* *environmental dangers*. University of California Press.

Doumont, J.-L. (2002) 'Magical Numbers: The Seven-Plus-or-Minus-Two Myth', *IEEE Transactions on Professional Communication*, 45(2), pp. 123–127.

Dow, K. and Cutter, S. L. (1998) 'Crying wolf: Repeat responses to hurricane evacuation orders', *Coastal Management*, 26(4), pp. 237–252. doi: 10.1080/08920759809362356.

Doyle, E. E. H. *et al.* (2011) 'The communication of uncertain scientific advice during natural hazard events', *New Zealand Journal of Psychology*, 40(4), pp. 39–50.

Doyle, E. E. H., McClure, J., Johnston, D. M., *et al.* (2014) 'Communicating likelihoods and probabilities in forecasts of volcanic eruptions', *Journal of Volcanology and Geothermal Research*. Elsevier B.V., 272, pp. 1–15. doi: 10.1016/j.jvolgeores.2013.12.006.

Doyle, E. E. H., McClure, J., Paton, D., *et al.* (2014) 'Uncertainty and decision making: Volcanic crisis scenarios', *International Journal of Disaster Risk Reduction*. Elsevier, 10(PA), pp. 75–101. doi: 10.1016/j.ijdrr.2014.07.006.

Doyle, E. E. H. *et al.* (2018) 'Motivations to prepare after the 2013 Cook Strait Earthquake, N.Z.', *International Journal of Disaster Risk Reduction*. Elsevier Ltd, 31(July), pp. 637–649. doi: 10.1016/j.ijdrr.2018.07.008.

Doyle, E. E. H. *et al.* (2020) 'Interpretations of aftershock advice and probabilities after the 2013 Cook Strait earthquakes, Aotearoa New Zealand', *International Journal of Disaster Risk Reduction*. Elsevier Ltd, 49, p. 101653. doi: 10.1016/j.ijdrr.2020.101653.

Doyle, E. and Potter, S. (2015) 'Methodology for the development of a probability translation table for GeoNet', *GNS Science Report*, 67(January), p. 18. Available at: https://www.dropbox.com/sh/couhc4qk7t0kbwf/AAAg0UTFO25WfiiqwNQ_cQV3a?dl=0&preview=Doyle_Potter_2016.pdf.

Driedger, S. M., Cooper, E. J. and Moghadas, S. M. (2014) 'Developing model-based public health policy through knowledge translation: The need for a "Communities of Practice"', *Public Health*. Elsevier Ltd, 128(6), pp. 561–567. doi: 10.1016/j.puhe.2013.10.009.

Dryhurst, S., Schneider, C. R., *et al.* (2020) 'Risk perceptions of COVID-19 around the world', *Journal of Risk Research*, pp. 1466–4461. doi: 10.1080/13669877.2020.1758193.

Dryhurst, S., van der Bles, A. M., *et al.* (2020) 'The effects of representing uncertainty around time series: COVID-19 mortality, polling trends and national statistics', *Preprint*.

Du, N. *et al.* (2011) 'The appeal of vague financial forecasts', *Organizational Behavior and Human Decision Processes*. Elsevier Inc., 114(2), pp. 179–189. doi: 10.1016/j.obhdp.2010.10.005.

Earl J. Baker (1991) 'Hurricane Evacuation Behavior', *International Journal of Mass Emergencies and Disasters*, 9(2), pp. 287–310. Available at: https://training.fema.gov/emiweb/downloads/ijems/articles/hurricane evacuation behavior.pdf.

Earle, T. and Cvetkovich, G. (1995) *Social Trust: Toward a Cosmopolitan Society.* Praeger.

Ecker, U. K. H., Hogan, J. L. and Lewandowsky, S. (2017) 'Reminders and Repetition of Misinformation: Helping or Hindering Its Retraction?', *Journal of Applied Research in Memory and Cognition*, 6(2), pp. 185–192. doi: 10.1016/j.jarmac.2017.01.014.

Ecker, U. K. H., Lewandowsky, S. and Chadwick, M. (2020) 'Can corrections spread misinformation to new audiences? Testing for the elusive familiarity backfire effect', *Cognitive Research: Principles and Implications*. Cognitive Research: Principles and Implications, 5(1). doi: 10.1186/s41235-020-00241-6.

Edwards, W. (1954) 'The theory of decision making.', *Psychological Bulletin*, 51(4), pp. 380–417.

De Elía, R. and Laprise, R. (2005) 'Diversity in interpretations of probability: Implications for weather forecasting', *Monthly Weather Review*, 133(5), pp. 1129–1143. doi: 10.1175/MWR2913.1.

Eppler, M. J. and Mengis, J. (2004) ‘The Concept of Information Overload - A Review of Literature from Organization Science, Accounting, Marketing, MIS, and Related Disciplines’, *The information Society: An International Journal*, 20(5), pp. 1–20. doi: 10.1007/978-3-8349-9772-2_15.

Evans, I. S. (1977) ‘The Selection of Class Intervals’, *Transactions of the Institute of British Geographers*, 2(1), p. 98. doi: 10.2307/622195.

Evans, J. S. B. T. (2003) ‘In two minds: Dual-process accounts of reasoning’, *Trends in Cognitive Sciences*. Elsevier Ltd, 7(10), pp. 454–459. doi: 10.1016/j.tics.2003.08.012.

Evans, J. S. B. T. (2008) ‘Dual-Processing Accounts of Reasoning, Judgment, and Social Cognition’, *Annual Review of Psychology*, 59(1), pp. 255–278. doi: 10.1146/annurev.psych.59.103006.093629.

Evans, J. S. B. T. (2011) ‘Dual-process theories of reasoning: Contemporary issues and developmental applications’, *Developmental Review*. Elsevier Inc., 31(2–3), pp. 86–102. doi: 10.1016/j.dr.2011.07.007.

Evans, J. S. B. T. and Stanovich, K. E. (2013) ‘Dual-Process Theories of Higher Cognition: Advancing the Debate’, *Perspectives on Psychological Science*, 8(3), pp. 223–241. doi: 10.1177/1745691612460685.

Fabrikant, S. I., Hespanha, S. R. and Hegarty, M. (2010) ‘Cognitively inspired and perceptually salient graphic displays for efficient spatial inference making’, *Annals of the Association of American Geographers*, 100(1), pp. 13–29. doi: 10.1080/00045600903362378.

Fallou, L. *et al.* (2020) ‘Citizen Seismology Without Seismologists? Lessons Learned From Mayotte Leading to Improved Collaboration’, *Frontiers in Communication*, 5(August), pp. 1–17. doi: 10.3389/fcomm.2020.00049.

Farrell, J., McConnell, K. and Brulle, R. (2019) ‘Evidence-based strategies to combat scientific misinformation’, *Nature Climate Change*. Springer US, 9(3), pp. 191–195. doi: 10.1038/s41558-018-0368-6.

Few, S. (2006) *Information Dashboard Design: The effective visual communication of data*. First Edit, *Information dashboard design: displaying data for at-a-glance monitoring*. First Edit. Edited by C. Wheeler. O’Reilly. Available at: https://books.google.de/books/about/Information_Dashboard_Design.html?id=7k0EnAEACAAJ&redir_esc=y.

Field, E. H. *et al.* (2016) ‘The potential uses of operational earthquake forecasting’, *Seismological Research Letters*, 87(2A), pp. 313–322. doi: 10.1785/0220150174.

Finucane, M. L. *et al.* (2000) ‘The Affect Heuristic in Judgments of Risks and Benfits’, *Journal of Behavioural Decision Making*, 17, pp. 1–17.

Fischer, D., Putzke-Hattori, J. and Fischbach, K. (2019) ‘Crisis Warning Apps: Investigating the Factors Influencing Usage and Compliance with Recommendations for Action’, *Proceedings of the 52nd Hawaii International Conference on System Sciences*, 6, pp. 639–648. doi: 10.24251/hicss.2019.079.

Fischhoff, B. *et al.* (1978) ‘How safe is safe enough? A psychometric study of attitudes towards technological risks and benefits’, *Policy Sciences*, 9(2), pp. 127–152. doi: 10.1007/BF00143739.

Fischhoff, B. (1994) ‘What forecasts (seem to) mean’, *International Journal of Forecasting*, 10, pp. 387–403.

Fischhoff, B. (2012) ‘Communicating Uncertainty: Fulfilling the Duty to Inform’, *Issues in Science and Technology*, 28(4), pp. 63–70.

Fischhoff, B. and MacGregor, D. (1983) ‘Judged Lethality: How Much People Seem to Know Depends Upon How They Are Asked’, *Risk Analysis*, 3(4), pp. 229–236. doi: 10.1111/j.1539-6924.1983.tb01391.x.

Fitzroy, R. (1863) *The weather book: a manual of practical meteorology*. Longman, Roberts & Green.

Forsythe, A. (2011) ‘The human factors of the conspicuous Babel fish; dyadic referencing through icons', *Journal of Visual Literacy*, 30(2), pp. 91–115. doi: 10.1080/23796529.2011.11674691.

Franklin, R. C. *et al.* (2014) '"Washed away"-assessing community perceptions of flooding and prevention strategies: A North Queensland example', *Natural Hazards*, 73(3), pp. 1977–1998. doi: 10.1007/s11069-014-1180-x.

Freeman, A. L. J., Kerr, J., *et al.* (2020) 'Communicating personalised risks from COVID-19: guidelines from an empirical study', *MedRxiv*. doi: https://doi.org/10.1101/2020.10.05.20206961.

Freeman, A. L. J., Schneider, C. R., *et al.* (2020) *Risk perception of COVID19/coronavirus*, *OSF project*. doi: 10.17605/OSF.IO/JNU74.

Freeman, D. *et al.* (2020) 'Coronavirus Conspiracy Beliefs, Mistrust, and Compliance with Government Guidelines in England', *Psychological Medicine*. 2020/05/21. Cambridge University Press, pp. 1–30. doi: DOI: 10.1017/S0033291720001890.

Fuchs, S. *et al.* (2009) 'Evaluating cartographic design in flood risk mapping', *Environmental Hazards*, 8(1), pp. 52–70. doi: 10.3763/ehaz.2009.0007.

Gaissmaier, W. *et al.* (2012) 'Numbers can be worth a thousand pictures: Individual differences in understanding graphical and numerical representations of health-related information', *Health Psychology*, 31(3), pp. 286–296. Available at: http://ovidsp.ovid.com/ovidweb.cgi?T=JS&PAGE=reference&D=medl&NEWS=N&AN=21842998%5Cnhttp://ovidsp.ovid.com/ovidweb.cgi?T=JS&PAGE=reference&D=emed14&NEWS=N&AN=368419079.

Gangarosa, E. J. *et al.* (1998) 'Impact of anti-vaccine movements on pertussis control: The untold story', *Lancet*, 351(9099), pp. 356–361. doi: 10.1016/S0140-6736(97)04334-1.

Gaspar-Escribano, J. M. and Iturrioz, T. (2011) 'Communicating earthquake risk: Mapped parameters and cartographic representation', *Natural Hazards and Earth System Science*, 11(2), pp. 359–366. doi: 10.5194/nhess-11-359-2011.

Geller, R. J. *et al.* (1997) 'Earthquakes Cannot Be Predicted', *Science*. American Association for the Advancement of Science, 275(5306), p. 1616. doi: 10.1126/science.275.5306.1616.

Geoscience Australia (2020) *Risk and Impact*, *Geoscience Australia*. Available at: https://www.ga.gov.au/scientific-topics/community-safety/risk-and-impact (Accessed: 28 November 2020).

German Red Cross (2018) *Report: 6th Global Dialogue Platform on Forecast-based Financing*. Available at: https://www.forecast-based-financing.org/wp-content/%0Auploads/2019/03/Report_DP18Berlin.pdf.

Gerstenberger, M. *et al.* (2014) 'Seismic hazard modeling for the recovery of christchurch', *Earthquake Spectra*, 30(1), pp. 17–29. doi: 10.1193/021913EQS037M.

Gerstenberger, M. C. *et al.* (2005) 'Real-time forecasts of tomorrow's earthquakes in California', *Nature*, 435(7040), pp. 328–331. doi: 10.1038/nature03622.

Gigerenzer, G. *et al.* (2005) '"A 30% chance of rain tomorrow": How does the public understand probabilistic weather forecasts?', *Risk Analysis*, 25(3), pp. 623–629. doi: 10.1111/j.1539-6924.2005.00608.x.

Gigerenzer, G. and Brighton, H. (2009) 'Homo Heuristicus: Why Biased Minds Make Better Inferences', *Topics in Cognitive Science*, 1(1), pp. 107–143. doi: 10.1111/j.1756-8765.2008.01006.x.

Gigerenzer, G. and Hoffrage, U. (1995) 'How to improve Bayesian reasoning without instruction: Frequency formats', *Psychological Review*, 102(4), pp. 684–704. doi: 10.1037/0033-295X.102.4.684.

Gladwin, H. *et al.* (2009) 'Social science research needs for the hurricane forecast and warning system', *Bulletin of the American Meteorological Society*, 90(1), pp. 25–29. doi: 10.1175/2008BAMS2606.1.

Goldsberry, K. and Battersby, S. (2009) 'Issues of change detection in animated choropleth maps', *Cartographica*, 44(3), pp. 201–215. doi: 10.3138/carto.44.3.201.

Goltz, J. D. (2015) 'A further note on operational earthquake forecasting: An emergency management perspective', *Seismological Research Letters*, 86(5), pp. 1231–1233. doi: 10.1785/0220150080.

Goltz, J., Russell, L. and Bourque, L. (1992) 'Initial Behavioral Response to a Rapid Onset Disaster: a Case Study of the October 1, 1987, Whittier Narrows Earthquake', *International journal of mass emergencies and disasters*, pp. 43–69.

Griffin, R. J. *et al.* (2008) 'After the Flood of Information', *Science communication*, (414), pp. 285–315.

Gschwandtner, T. *et al.* (2016) 'Visual Encodings of Temporal Uncertainty: A Comparative User Study', *IEEE Transactions on Visualization and Computer Graphics*, 22(1), pp. 539–548. doi: 10.1109/TVCG.2015.2467752.

Hagemeier-Klose, M. and Wagner, K. (2009) 'Evaluation of flood hazard maps in print and web mapping services as information tools in flood risk communication', *Natural Hazards and Earth System Science*, 9(2), pp. 563–574. doi: 10.5194/nhess-9-563-2009.

Halpern, D. F., Blackman, S. and Salzman, B. (1989) 'Using statistical risk information to assess oral contraceptive safety', *Applied Cognitive Psychology*, 3(3), pp. 251–260. doi: 10.1002/acp.2350030305.

Han, P. K. J., Klein, W. M. P. and Arora, N. K. (2011) 'Varieties of Uncertainty in Health Care: A Conceptual Taxonomy', *Medical Decision Making*, 31(6), pp. 828–838. doi: 10.1177/0272989X11393976.

Handmer, J. (2001) 'Improving flood warnings in europe: A research and policy agenda', *Environmental Hazards*, 3(1), pp. 19–28. doi: 10.3763/ehaz.2001.0302.

Handmer, J. and Proudley, B. (2007) 'Communicating uncertainty via probabilities: The case of weather forecasts', *Environmental Hazards*, 7(2), pp. 79–87. doi: 10.1016/j.envhaz.2007.05.002.

Hansen, J., Marx, S. and Weber, E. (2004) *The Role of Climate Perceptions, Expectations, and Forecasts in Farmer Decision Making: The Argentine Pampas and South Florida*, *The International Research Institute for Climate Prediction*. doi: https://doi.org/10.7916/D8N01DC6.

Harris, A. J. L. *et al.* (2013) 'Lost in translation? Interpretations of the probability phrases used by the Intergovernmental Panel on Climate Change in China and the UK', *Climatic Change*, 121(2), pp. 415–425. doi: 10.1007/s10584-013-0975-1.

Harris, A. J. L. and Corner, A. (2011) 'Communicating environmental risks: Clarifying the severity effect in interpretations of verbal probability expressions', *Journal of Experimental Psychology: Learning, Memory, and Cognition*. Harris, Adam J. L., Department of Cognitive, Perceptual and Brain Sciences, University College London, London, United Kingdom, WC1H 0AP: American Psychological Association, 37(6), pp. 1571–1578. doi: 10.1037/a0024195.

Harrower, M. (2007) 'The cognitive limits of animated maps', *Cartographica*, 42(4), pp. 349–357. doi: 10.3138/carto.42.4.349.

Hegarty, M. (2011) 'The cognitive science of visual-spatial displays: Implications for design', *Topics in Cognitive Science*, 3(3), pp. 446–474. doi: 10.1111/j.1756-8765.2011.01150.x.

Hegarty, M., Canham, M. S. and Fabrikant, S. I. (2010) 'Thinking About the Weather: How Display Salience and Knowledge Affect Performance in a Graphic Inference Task', *Journal of Experimental Psychology: Learning Memory and Cognition*, 36(1), pp. 37–53. doi: 10.1037/a0017683.

Heller, K. *et al.* (2005) 'Social and personal factors as predictors of earthquake preparation: The role of support provision, network discussion, negative affect, age, and education', *Journal of Applied Social Psychology*, 35(2), pp. 399–422. doi: 10.1111/j.1559-1816.2005.tb02127.x.

Henrich, L., McClure, J. and Crozier, M. (2015) 'Effects of risk framing on earthquake risk perception:

Life-time frequencies enhance recognition of the risk', *International Journal of Disaster Risk Reduction*. Elsevier, 13, pp. 145–150. doi: 10.1016/j.ijdrr.2015.05.003.

Hertwig, R. *et al.* (2004) 'Decisions from experience and the effect of rare events in risky choice', *Psychological Science*, 15(8), pp. 534–539. doi: 10.1111/j.0956-7976.2004.00715.x.

Hirschberg, P. A. *et al.* (2011) 'Strategic Implementation Plan for Generating and Communicating Forecast Uncertainty', (DECember), pp. 1651–1666. doi: 10.1175/BAMS-D-10-00073.1.

Hofman, J. M., Goldstein, D. G. and Hullman, J. (2020) 'How Visualizing Inferential Uncertainty Can Mislead Readers About Treatment Effects in Scientific Results', pp. 1–12. doi: 10.1145/3313831.3376454.

Holmsen, A. *et al.* (2008) *Communicating Monetary Policy Intentions: The Case of Norges Bank*, *Working paper No. 2008/20, Norges Bank, Oslo*. Available at: https://eprints.lib.hokudai.ac.jp/dspace/bitstream/2115/39616/1/JESW15_003.pdf.

Hughes, A. L. *et al.* (2014) 'Online public communications by police & fire services during the 2012 Hurricane Sandy', *Conference on Human Factors in Computing Systems - Proceedings*, pp. 1505–1514. doi: 10.1145/2556288.2557227.

Hullman, J. (2020) 'Why Authors Don't Visualize Uncertainty', *IEEE Transactions on Visualization and Computer Graphics*, 26(1), pp. 130–139.

Hullman, J., Resnick, P. and Adar, E. (2015) 'Hypothetical outcome plots outperform error bars and violin plots for inferences about reliability of variable ordering', *PLoS ONE*, 10(11), pp. 1–25. doi: 10.1371/journal.pone.0142444.

Hunt, K., Wang, B. and Zhuang, J. (2020) 'Misinformation debunking and cross-platform information sharing through Twitter during Hurricanes Harvey and Irma: a case study on shelters and ID checks', *Natural Hazards*. Springer Netherlands, 103(1), pp. 861–883. doi: 10.1007/s11069-020-04016-6.

Hyvärinen, O. and Saltikoff, E. (2010) 'Social media as a source of meteorological observations', *Monthly Weather Review*, 138(8), pp. 3175–3184. doi: 10.1175/2010MWR3270.1.

Ibrekk, H. and Morgan, M. G. (1987) 'Graphical Communication of Uncertain Quantities to Nontechnical People', *Risk Analysis*, 7(4), pp. 519–529. doi: 10.1111/j.1539-6924.1987.tb00488.x.

Iervolino, I. *et al.* (2015) 'Operational (short-term) earthquake loss forecasting in Italy', *Bulletin of the Seismological Society of America*, 105(4), pp. 2286–2298. doi: 10.1785/0120140344.

Ioannou, I. *et al.* (2018) 'Empirical seismic vulnerability assessment of Icelandic buildings affected by the 2000 sequence of earthquakes', *Bulletin of Earthquake Engineering*. Springer Netherlands, 16(12), pp. 5875–5903. doi: 10.1007/s10518-018-0413-x.

IPCC (2014) *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, *IPCC*. Edited by Core Writing Team, R. K. Pachauri, and L. A. Meyer. Geneva, Switzerland. doi: 10.2307/1881805.

Jackson, E. L. (1981) 'Response to earthquake hazard: The West Coast of North America.', *Environment and Behavior*, 13, pp. 387–416.

Jackson, E. L. and Mukerjee, T. (1974) 'Human adjustment to the earthquake hazard of San Francisco', in White, G. (ed.) *Natural hazards: Local, national and global*. New York: Oxford University Press, pp. 160–166.

Jeffrey, R. C. (1983) *The Logic of Decision*. 2nd edn. University of Chicago Press.

Jenkins, S. C., Harris, A. J. L. and Lark, R. M. (2018) 'Understanding "Unlikely (20% Likelihood)" or "20% Likelihood (Unlikely)" Outcomes: The Robustness of the Extremity Effect', *Journal of Behavioral Decision Making*, 31(4), pp. 572–586. doi: 10.1002/bdm.2072.

Joffe, H. (2003) 'Risk: From perception to social representation', *British Journal of Social Psychology*, 42(1), pp. 55–73. doi: 10.1348/014466603763276126.

Johnson, B. B. and Slovic, P. (1995) ‘Presenting uncertainty in health risk assessment: initial studies of its effects on risk perception and trust.’, *Risk Analysis*, 15(4), pp. 485–494. doi: 10.1111/j.1539-6924.1995.tb00341.x.

Johnson, B. B. and Slovic, P. (1998) ‘Lay views on uncertainty in environmental health risk assessment’, *Journal of Risk Research*, 1(4), pp. 261–279. doi: 10.1080/136698798377042.

Johnson, E. B. *et al.* (1993) ‘Framing, Probability Distortions, and Insurance Decisions’, *Journal of Risk and Uncertainty*, 7, pp. 35–51.

Jolley, D. and Paterson, J. L. (2020) ‘Pylons ablaze: Examining the role of 5G COVID-19 conspiracy beliefs and support for violence’, *British Journal of Social Psychology*, 59(3), pp. 628–640. doi: 10.1111/bjso.12394.

Jones, E. C. *et al.* (2013) ‘Cross-Cultural and Site-Based Influences on Demographic, Well-being, and Social Network Predictors of Risk Perception in Hazard and Disaster Settings in Ecuador and Mexico: Predictors of Risk Perception in Hazard and Disaster Settings in Ecuador and Mexic’, *Human Nature*, 24(1), pp. 5–32. doi: 10.1007/s12110-013-9162-3.

Jordan, T. H. *et al.* (2011) ‘Operational earthquake forecasting: State of knowledge and guidelines for utilization’, *Annals of Geophysics*, 54(4), pp. 319–391. doi: 10.4401/ag-5350.

Jordan, T. H. (2013a) ‘Lessons of l’aquila for operational earthquake forecasting’, *Seismological Research Letters*, 84(1), pp. 4–7. doi: 10.1785/0220120167.

Jordan, T. H. (2013b) ‘Lessons of l’Aquila for operational earthquake forecasting’, *Seismological Research Letters*, 84(1), pp. 4–7. doi: 10.1785/0220120167.

Jordan, T. H. *et al.* (2014) ‘Operational earthquake forecasting can enhance earthquake preparedness’, *Seismological Research Letters*, 85(5), pp. 955–959. doi: 10.1785/0220140143.

Joslyn, S. *et al.* (2007) ‘The effect of probabilistic information on threshold forecasts’, *Weather and Forecasting*, 22(4), pp. 804–812. doi: 10.1175/WAF1020.1.

Joslyn, S. L. and LeClerc, J. E. (2012) ‘Uncertainty forecasts improve weather-related decisions and attenuate the effects of forecast error’, *Journal of Experimental Psychology: Applied*, 18(1), pp. 126–140. doi: 10.1037/a0025185.

Joslyn, S. L. and LeClerc, J. E. (2013) ‘Decisions With Uncertainty: The Glass Half Full’, *Current Directions in Psychological Science*, 22(4), pp. 308–315. doi: 10.1177/0963721413481473.

Joslyn, S., Nadav-greenberg, L. and Nichols, R. M. (2009) ‘Probability of Precipitation’, *Bulletin of the American Meteorological Society*, 90(2), pp. 185–193. doi: 10.1175/2008BAMS2509.I.

Joslyn, S. and Savelli, S. (2010) ‘Communicating forecast uncertainty: Public perception of weather forecast uncertainty’, *Meteorological Applications*, 17(2), pp. 180–195. doi: 10.1002/met.190.

Juanchich, M. and Sirota, M. (2016) ‘How to improve people’s interpretation of probabilities of precipitation’, *Journal of Risk Research*. Routledge, 19(3), pp. 388–404. doi: 10.1080/13669877.2014.983945.

Julia Becker *et al.* (2015) ‘Aftershock communication during the Canterbury Earthquakes, New Zealand: Implications for response and recovery in the built environment’, in. Available at: http://pubs.er.usgs.gov/publication/70148058.

Kahan, D. M. *et al.* (2012) ‘The polarizing impact of science literacy and numeracy on perceived climate change risks’, *Nature Climate Change*. Nature Publishing Group, 2(10), pp. 732–735. doi: 10.1038/nclimate1547.

Kahneman, D. (2011) *Thinking, fast and slow*. Macmillan.

Kahneman, D. and Tversky, A. (1979) ‘Prospect theory: An analysis of decision under risk. Econometrika, 47, 263-291.’, *Econometrica*, 47(2), pp. 263–292.

Kane, M. J. and Engle, R. W. (2003) ‘Working-Memory Capacity and the Control of Attention: The

Contributions of Goal Neglect, Response Competition, and Task Set to Stroop Interference', *Journal of Experimental Psychology: General*, 132(1), pp. 47–70. doi: 10.1037/0096-3445.132.1.47.

Kaplan, R. M., Hammel, B. and Schimmel, L. E. (1985) 'Patient information processing and the decision to accept treatment.', *Journal of social behavior and personality*, 1(1), pp. 113–120.

Kapucu, N. (2008) 'Culture of preparedness: Household disaster preparedness', *Disaster Prevention and Management: An International Journal*, 17(4), pp. 526–535. doi: 10.1108/09653560810901773.

Karl, I., Rother, K. and Nestler, S. (2015) 'Crisis-Related Apps: Assistance for critical and emergency situations', *International Journal of Information Systems for Crisis Response and Management*, 7(2), pp. 19–35. doi: 10.4018/ijiscram.2015040102.

Kashefi, E. *et al.* (2009) *Communication and dissemination of probabilistic flood warnings - Final report*, *Environment Agency/Defra Flood and Coastal Erosion Risk Management Research & Development Programme*. doi: 10.1007/978-3-319-65581-9_22.

Kasperson, R. E. *et al.* (2016) 'The social amplification of risk: A conceptual framework', *The Perception of Risk*, 8(2), pp. 232–245. doi: 10.1111/j.1539-6924.1988.tb01168.x.

Kates, R. and White, G. (1961) 'Flood hazard evaluation.', in White, G. (ed.) *Papers on Flood Problems: Department of Geography Research Paper No. 70.* Chicago: University of Chicago Press, pp. 135–147.

Kaufhold, M. A. *et al.* (2018) 'Design and evaluation of a mobile crisis app for bidirectional communication between emergency services and citizens', *26th European Conference on Information Systems: Beyond Digitization - Facets of Socio-Technical Change: Research Papers*, 81, p. 112 (social).

Keeling, S. J. (2010) 'Visualization of the weather - Past and present', *Meteorological Applications*, 17(2), pp. 126–133. doi: 10.1002/met.208.

Keith V . Nesbitt, S. B. (2006) 'Evaluation of a Multimodal Sonification and Visualisation of Depth of Market Stock Data', *Proceedings of the 2002 International Conference on Auditory Display, Kyoto, Japan, July 2-5, 2002*, pp. 1–6.

Kellens, W. *et al.* (2013) 'Perception and Communication of Flood Risks: A Systematic Review of Empirical Research', *Risk Analysis*, 33(1), pp. 24–49. doi: 10.1111/j.1539-6924.2012.01844.x.

Keller, C., Siegrist, M. and Gutscher, H. (2006) 'The role of the affect and availability heuristics in risk communication', *Risk Analysis*, 26(3), pp. 631–639. doi: 10.1111/j.1539-6924.2006.00773.x.

Keller, P. A., Lipkus, I. M. and Rimer, B. K. (2003) 'Affect, framing, and persuasion.', *Journal of Marketing Research*, 40(1), pp. 54–64.

Kjellgren, S. (2013) 'Exploring local risk managers' use of flood hazard maps for risk communication purposes in Baden-Württemberg', *Natural Hazards and Earth System Sciences*, 13(7), pp. 1857–1872. doi: 10.5194/nhess-13-1857-2013.

Klemm, T. and McPherson, R. A. (2017) 'The development of seasonal climate forecasting for agricultural producers', *Agricultural and Forest Meteorology*. Elsevier B.V., 232, pp. 384–399. doi: 10.1016/j.agrformet.2016.09.005.

Kosslyn, S. M. (1989) 'Understanding charts and graphs', *Applied Cognitive Psychology*, 3(3), pp. 185–225. doi: 10.1002/acp.2350030302.

Kotthaus, C., Ludwig, T. and Pipek, V. (2016) 'Persuasive system design analysis of mobile warning apps for citizens', *CEUR Workshop Proceedings*, 1817.

Kovesi, P. (2015) 'Good Colour Maps: How to Design Them', pp. 1–42. Available at: http://arxiv.org/abs/1509.03700.

Kreibich, H. *et al.* (2009) 'Extent, perception and mitigation of damage due to high groundwater levels in the city of Dresden, Germany', *Natural Hazards and Earth System Science*, 9(4), pp. 1247–1258. doi: 10.5194/nhess-9-1247-2009.

Kuhn, K. M. (2000) 'Message format and audience values: Interactive effects of uncertainty information and environmental attitudes on perceived risk', *Journal of Environmental Psychology*, 20(1), pp. 41–51. doi: 10.1006/jevp.1999.0145.

Kunda, Z. (1990) 'The Case for Motivated Reasoning', *Psychological Bulletin*, 108(3), pp. 480–498.

Kunreuther, H. *et al.* (1978) *Disaster insurance protection: Public policy lessons.* New York: John Wiley.

Kunz, M., Grêt-Regamey, A. and Hurni, L. (2011) 'Customized Visualization of Natural Hazards Assessment Results and Associated Uncertainties through Interactive Functionality', *Cartography and Geographic Information Science*, 38(2), pp. 232–242. doi: 10.1559/15230406382232.

Lang, J. T. and Hallman, W. K. (2005) 'Who does the public trust? The case of genetically modified food in the United States', *Risk Analysis*, 25(5), pp. 1241–1252.

Lasswell, H. D. (1948) 'The Structure and Function of Communication in Society', in Bryson, L. (ed.) *The Communication of Ideas*. New York: Harper, pp. 37–51.

Lazrus, H. *et al.* (2016) '"Know What to Do If You Encounter a Flash Flood": Mental Models Analysis for Improving Flash Flood Risk Communication and Public Decision Making', *Risk Analysis*, 36(2), pp. 411–427. doi: 10.1111/risa.12480.

Lee, T. (2019) 'The global rise of "fake news" and the threat to democratic elections in the USA', *Public Administration and Policy*, 22(1), pp. 15–24. doi: 10.1108/pap-04-2019-0008.

Leiserowitz, A. (2006) 'Climate change risk perception and policy preferences: The role of affect, imagery, and values', *Climatic Change*, 77(1–2), pp. 45–72. doi: 10.1007/s10584-006-9059-9.

Lemos, M. C., Kirchhoff, C. J. and Ramprasad, V. (2012) 'Narrowing the climate information usability gap', *Nature Climate Change*, 2(11), pp. 789–794. doi: 10.1038/nclimate1614.

Lewandowsky, S., Ecker, Ullrich K. H., *et al.* (2012) 'Misinformation and its correction: Continued influence and successful debiasing', *Psychological Science in the Public Interest*, 13(3), pp. 106–131. doi: 10.1177/1529100612451018.

Lewandowsky, S., Ecker, Ullrich K.H., *et al.* (2012) 'Misinformation and Its Correction: Continued Influence and Successful Debiasing', *Psychological Science in the Public Interest, Supplement*, 13(3), pp. 106–131. doi: 10.1177/1529100612451018.

Lewandowsky, S., Ecker, U. K. H. and Cook, J. (2017) 'Beyond Misinformation: Understanding and Coping with the "Post-Truth" Era', *Journal of Applied Research in Memory and Cognition*, 6(4), pp. 353–369. doi: 10.1016/j.jarmac.2017.07.008.

Lindell, M. K. *et al.* (2016) 'Perceptions and expected immediate reactions to tornado warning polygons', *Natural Hazards*. Springer Netherlands, 80(1), pp. 683–707. doi: 10.1007/s11069-015-1990-5.

Lindell, M. K. and Perry, R. W. (2012) 'The Protective Action Decision Model: Theoretical Modifications and Additional Evidence', *Risk Analysis*, 32(4), pp. 616–632. doi: 10.1111/j.1539-6924.2011.01647.x.

Lindell, M. K. and Prater, C. S. (2000) 'Household Adoption of Seismic Hazard Adjustments: A Comparison of Residents in Two States', *International journal of mass emergencies and disasters*, 18(2), pp. 317–338. Available at: http://dx.doi.org/.

van der Linden, S. (2015) 'The social-psychological determinants of climate change risk perceptions: Towards a comprehensive model', *Journal of Environmental Psychology*. van der Linden, Sander, Department of Psychology, Princeton University, Peretsman-Scully Hall 421, Princeton, NJ, US, 08544: Elsevier Science, 41, pp. 112–124. doi: 10.1016/j.jenvp.2014.11.012.

van der Linden, S. (2017) *Determinants and Measurement of Climate Change Risk Perception, Worry, and Concern*, *Oxford Research Encyclopedia of Climate Science*. doi: 10.1093/acrefore/9780190228620.013.318.

van der Linden, S. *et al.* (2017a) 'Inoculating the Public against Misinformation about Climate Change', *Global Challenges*, 1(2), p. 1600008. doi: 10.1002/gch2.201600008.

van der Linden, S. *et al.* (2017b) 'Inoculating the Public against Misinformation about Climate Change', *Global Challenges*, 1(2), p. 1600008. doi: 10.1002/gch2.201600008.

Linden, S. Van Der *et al.* (2017) 'Inoculating against misinformation', *Science*, 358(6367), pp. 1141–1142.

Linden, S. van der and Löfstedt, R. E. (eds) (2019) *Risk and Uncertainty in a Post-Truth Society*. London, UK: Routledge. doi: 10.4324/9780429280290.

van der Linden, S., Panagopoulos, C. and Roozenbeek, J. (2020) 'You are fake news: the emergence of political bias in perceptions of fake news', *Media, Culture & Society*, 1(11). doi: 10.1177/0163443720906992.

van der Linden, S. and Roozenbeek, J. (2020) 'Psychological Inoculation Against Fake News', *The Psychology of Fake News*, (August), pp. 147–169. doi: 10.4324/9780429295379-11.

Linville, P. W. and Fischer, G. W. (1991) 'Preferences for Separating or Combining Events', *Journal of Personality and Social Psychology*, 60(1), pp. 5–23. doi: 10.1037/0022-3514.60.1.5.

Lipkus, I. M. (2007) 'Numeric, verbal, and visual formats of conveying health risks: suggesting best practices and future recommendations', *Medical Decision Making*. Lipkus, Isaac M., Duke University Medical Center, Department of Psychiatry, 905 West Main Street, Box 34, Durham, NC, US, 27701: Sage Publications, 27(5), pp. 696–713. doi: 10.1177/0272989X07307271.

Lipkus, I. M. and Hollands, J. G. (1999) 'The visual communication of risk.', *Journal of the National Cancer Institute. Monographs*, 27701(25), pp. 149–63. doi: 10.1093/oxfordjournals.jncimonographs.a024191.

Loewenstein, G. F. *et al.* (2001) 'Risk As Feelings', *Psychological Bulletin*, 127(2), pp. 267–286. doi: http://dx.doi.org/10.1037/0033-2909.127.2.267.

Maduz, L. *et al.* (2019) *Individual Disaster Preparedness: Explaining disaster-related information-seeking and preparedness behavior in Switzerland*. Zürich. doi: https://doi.org/10.3929/ethz-b-000356695.

Maertens, R., Anseel, F. and van der Linden, S. (2020) 'Combatting climate change misinformation: Evidence for longevity of inoculation and consensus messaging effects', *Journal of Environmental Psychology*. Elsevier Ltd, 70(May), p. 101455. doi: 10.1016/j.jenvp.2020.101455.

De Man, A. D. E. and Simpson-Housley, P. (1987) 'Factors in perception of earthquake hazard.', *Perceptual and Motor Skills*, pp. 815–820.

Manski, C. F. (2018) *The lure of incredible certitude*, *Northwestern Institute for Policy Research*. doi: 10.1017/S0266267119000105.

Marti, M. *et al.* (2018) 'Communicating Earthquake Preparedness: The Influence of Induced Mood, Perceived Risk, and Gain or Loss Frames on Homeowners' Attitudes Toward General Precautionary Measures for Earthquakes', *Risk Analysis*, 38(4), pp. 710–723. doi: 10.1111/risa.12875.

Marti, M., Stauffacher, M. and Wiemer, S. (2019) 'Difficulties in explaining complex issues with maps: Evaluating seismic hazard communication - The Swiss case', *Natural Hazards and Earth System Sciences*, 19(12), pp. 2677–2700. doi: 10.5194/nhess-19-2677-2019.

Marti, M., Stauffacher, M. and Wiemer, S. (2020) 'Anecdotal evidence is an insufficient basis for designing earthquake preparedness campaigns', *Seismological Research Letters*, 91(4), pp. 1929–1935. doi: 10.1785/0220200010.

Marzocchi, W., Taroni, M. and Falcone, G. (2017) 'Earthquake forecasting during the complex Amatrice-Norcia seismic sequence', *Science Advances*, 3(9), pp. 1–8. doi: 10.1126/sciadv.1701239.

Mason, J. B. and Senkbeil, J. C. (2015) 'A tornado watch scale to improve public response', *Weather, Climate, and Society*, 7(2), pp. 146–158. doi: 10.1175/WCAS-D-14-00035.1.

Mayer, R. E. and Chandler, P. (2001) 'When learning is just a click away: does simple user interaction foster deeper understanding of multimedia messages?', *Journal of Education Psychology*, 93(2), pp. 390–397.

McBride, S. K. *et al.* (2018) 'Developing earthquake forecast templates for fast and effective communication', *11th National Conference on Earthquake Engineering 2018, NCEE 2018: Integrating Science, Engineering, and Policy*, 12(September 2019), pp. 7310–7316.

McBride, S. K. *et al.* (2019) '#earthquakeAdvisory: Exploring discourse between government officials, news media, and social media during the 2016 Bombay beach swarm', *Seismological Research Letters*, 91(1), pp. 438–451. doi: 10.1785/0220190082.

McBride, S. K. *et al.* (2020) 'Developing post-alert messaging for ShakeAlert, the earthquake early warning system for the West Coast of the United States of America', *International Journal of Disaster Risk Reduction*. Elsevier Ltd, 50(May), p. 101713. doi: 10.1016/j.ijdrr.2020.101713.

McClelland, G. H., Schulze, W. D. and Coursey, D. L. (1993) 'Insurance for low-probability hazards: A bimodal response to Unlikely Events', *Journal of Risk and Uncertainty*, 7, pp. 95–116. doi: 10.1007/978-94-011-2192-7_7.

McClelland, G. H., Schulze, W. D. and Hurd, B. (1990) 'The Effect of Risk Beliefs on Property Values: A Case Study of a Hazardous Waste Site', *Risk Analysis*, 10(4), pp. 485–497. doi: 10.1111/j.1539-6924.1990.tb00534.x.

McClure, J., Doyle, E. E. H. and Velluppillai, J. M. (2015) 'A tale of two cities: Judgments about earthquake and aftershock probabilities across time windows', *International Journal of Disaster Risk Reduction*. Elsevier, 14, pp. 15–26. doi: 10.1016/j.ijdrr.2014.11.010.

McClure, J. and Sibley, C. G. (2011) 'Framing effects on disaster preparation: Is negative framing more effective?', *Australasian Journal of Disaster and Trauma Studies*, 2011(1).

McClure, J., White, J. and Sibley, C. G. (2009) 'Framing effects on preparation intentions: Distinguishing actions and outcomes', *Disaster Prevention and Management: An International Journal*, 18(2), pp. 187–199. doi: 10.1108/09653560910953252.

McGuire, W. J. (1970) 'A vaccine for brainwash', *Psychology Today*, 3(9), pp. 36–64.

Michael, A. J. *et al.* (2019) 'Statistical seismology and communication of the USGS operational aftershock forecasts for the 30 November 2018 Mw 7.1 Anchorage, Alaska, earthquake', *Seismological Research Letters*, 91(1), pp. 153–173. doi: 10.1785/0220190196.

Mileti, D. (1995) 'Factors related to flood warning response', *… , Impacts, and Management of Extreme Floods, …*, (November), pp. 1–17. Available at: http://www.engr.colostate.edu/~jsalas/us-italy/papers/46mileti.pdf.

Mileti, D. and Fitzpatrick, C. (1993) *The Great Earthquake Prediction Experiment: Risk Communication and Public Action*. Boulder, CO: Westview.

Mileti, D. S. *et al.* (1991) 'Public perception and response to the Parkfield California Earthquake prediction', in Garrick, B. J. and Gekler, W. C. (eds) *The Analysis, Communication, and Perception of Risk.* Boston, MA, MA: Springer.

Mileti, D. S. *et al.* (2004) 'Public Hazards Communication and Education: The State of the Art', *Informer*, 11(2), pp. 359–366. Available at: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3693708&tool=pmcentrez&rendertype=abstract%5Cn%3CGo to ISI%3E://WOS:A1991BT16Z00032%5Cnhttp://link.springer.com/10.1007/978-94-007-1433-5%5Cnhttp://www.tandfonline.com/doi/abs/10.1207/s15327590ijhc.

Mileti, D. S. and Darlington, J. D. (1995) 'Societal Response to Revised Earthquake Probabilities in the San Francisco Bay Area', *International Journal of Mass Emergencies and Disasters*, 13(2), pp. 119–145.

Mileti, D. S. and Darlington, J. D. (1997a) 'The role of searching in shaping reactions to earthquake risk information', *Social Problems*, 44(1), pp. 89–103. doi: 10.2307/3096875.

Mileti, D. S. and Darlington, J. D. (1997b) 'The role of searching in shaping reactions to earthquake risk information', *Social Problems*, 44(1), pp. 89–103. doi: 10.2307/3096875.

Mileti, D. S. and Fitzpatrick, C. (1992) 'The Causal Sequence of Risk Communication in the Parkfield Earthquake Prediction Experiment', *Risk Analysis*, 12(3), pp. 393–400. doi: 10.1111/j.1539-6924.1992.tb00691.x.

Mileti, D. S. and O'Brien, P. W. (1992) 'Warnings during Disaster: Normalizing Communicated Risk', *Social Problems*, 39(1), pp. 40–57.

Mileti, D. S. and Sorensen, J. H. (1987) 'Natural hazards and precautionary behavior.', in *Taking care: Understanding and encouraging self-protective behavior.* New York, NY, US, NY, US: Cambridge University Press, pp. 189–207. doi: 10.1017/CBO9780511527760.012.

Milfont, T. L., Wilson, J. and Diniz, P. (2012) 'Time perspective and environmental engagement: A meta-analysis', *International Journal of Psychology*, 47(5), pp. 325–334. doi: 10.1080/00207594.2011.647029.

Miller, S. (2007) 'Design of Multimedia Mapping Products', in *Multimedia Cartography*. Springer Verlag Heidelberg, pp. 89–104.

Millet, B. *et al.* (2020) 'Hurricane risk communication: Visualization and behavioral science concepts', *Weather, Climate, and Society*, 12(2), pp. 193–211. doi: 10.1175/WCAS-D-19-0011.1.

Miran, S. M., Ling, C. and Rothfusz, L. (2018) 'Factors influencing people's decision-making during three consecutive tornado events', *International Journal of Disaster Risk Reduction*. Elsevier Ltd, 28(February), pp. 150–157. doi: 10.1016/j.ijdrr.2018.02.034.

Moghadas, S. M. *et al.* (2015) 'Improving public health policy through infection transmission modelling: Guidelines for creating a community of practice', *Canadian Journal of Infectious Diseases and Medical Microbiology*, 26(4), pp. 191–195. doi: 10.1155/2015/274569.

Morss, R. E. *et al.* (2008) 'Communicating Uncertainty in Weather Forecasts: A Survey of the U.S. Public', *Weather and Forecasting*, 23(5), pp. 974–991. doi: 10.1175/2008WAF2007088.1.

Morss, R. E. *et al.* (2015) 'Flash Flood Risks and Warning Decisions: A Mental Models Study of Forecasters, Public Officials, and Media Broadcasters in Boulder, Colorado', *Risk Analysis*, 35(11), pp. 2009–2028. doi: 10.1111/risa.12403.

Morss, R. E. *et al.* (2016) 'How do people perceive, understand, and anticipate responding to flash flood risks and warnings? Results from a public survey in Boulder, Colorado, USA', *Journal of Hydrology*. Elsevier B.V., 541, pp. 649–664. doi: 10.1016/j.jhydrol.2015.11.047.

Morss, R. E. *et al.* (2017) 'Hazardous weather prediction and communication in the modern information environment', *Bulletin of the American Meteorological Society*, 98(12), pp. 2653–2674. doi: 10.1175/BAMS-D-16-0058.1.

Morss, R. E. and Hayden, M. H. (2010) 'Storm surge and "certain death": Interviews with texas coastal residents following hurricane ike', *Weather, Climate, and Society*, 2(3), pp. 174–189. doi: 10.1175/2010WCAS1041.1.

Nadav-Greenberg, L. and Joslyn, S. L. (2009) 'Uncertainty Forecasts Improve Decision Making Among Nonexperts', *Journal of Cognitive Engineering and Decision Making*, 3(3), pp. 209–227. doi: 10.1518/155534309X474460.

Neuhoff, J. G. *et al.* (2000) 'Sonification and the Interaction of Perceptual Dimensions : Can the Data Get Lost in the Map ?', in *International Conference on Auditory Display*.

von Neumann, J. and Morgenstern, O. (1944) *Theory of games and economic behavior.* Princeton University Press.

Newman, G. E. and Scholl, B. J. (2012) 'Bar graphs depicting averages are perceptually misinterpreted: The within-the-bar bias', *Psychonomic Bulletin and Review*, 19(4), pp. 601–607. doi: 10.3758/s13423-012-0247-5.

Nkiaka, E. *et al.* (2019) 'Identifying user needs for weather and climate services to enhance resilience to climate shocks in sub-Saharan Africa', *Environmental Research Letters*. IOP Publishing, 14(12). doi: 10.1088/1748-9326/ab4dfe.

NRC (2008) *Completing the Forecast: Characterizing and Communicating Uncertainty for Better Decisions Using Weather and Climate Forecasts*. Washington, D.C., D.C.

O'Neill, O. (2014) 'Trust, trustworthiness, and accountability', in *Capital failure: Rebuilding trust in financial services*, pp. 172–189.

Oreskes, N. and Conway, E. M. (2010) 'Defeating the merchants of doubt', *Nature*, 465(7299), pp. 686–687. doi: 10.1038/465686a.

Oxman, A. D. *et al.* (2020) 'Development of a checklist for people communicating evidence- - based information about the effects of healthcare interventions : a mixed methods study', pp. 1–9. doi: 10.1136/bmjopen-2019-036348.

Padilla, L. M. K., Creem-Regehr, S. H. and Thompson, W. (2020) 'The powerful influence of marks: Visual and knowledge-driven processing in hurricane track displays', *Journal of experimental psychology. Applied*, 26(1), pp. 1–15. doi: 10.1037/xap0000245.

Padilla, L. M., Ruginski, I. T. and Creem-Regehr, S. H. (2017) 'Effects of ensemble and summary displays on interpretations of geospatial uncertainty data', *Cognitive Research: Principles and Implications*. Cognitive Research: Principles and Implications, 2(1), pp. 1–16. doi: 10.1186/s41235-017-0076-1.

Painter, J. and Gavin, N. T. (2016) 'Climate Skepticism in British Newspapers, 2007–2011', *Environmental Communication*. Taylor & Francis, 10(4), pp. 432–452. doi: 10.1080/17524032.2014.995193.

Paling, J. (2003) 'Strategies to help patients understand risks', *Bmj*, 327(7417), pp. 745–748. doi: 10.1136/bmj.327.7417.745.

Palm, R. *et al.* (1990) *Earthquake insurance in California.* Boulder, CO, CO: Westview.

Parker, D. J. and Handmer, J. W. (1998) 'The role of unofficial flood warning systems', *Journal of Contingencies and Crisis Management*, 6(1), pp. 45–60. doi: 10.1111/1468-5973.00067.

Paton, D. (2007) 'Preparing for natural hazards: the role of community trust', *Disaster prevention and management : an international journal.* Bradford :, pp. 370–379. doi: 10.1108/09653560710758323.

Paton, D. *et al.* (2010) 'Making sense of natural hazard mitigation: Personal, social and cultural influences', *Environmental Hazards*, 9(2), pp. 183–196. doi: 10.3763/ehaz.2010.0039.

Paton, D. *et al.* (2015) 'Developing a comprehensive model of hazard preparedness: Lessons from the Christchurch earthquake', *International Journal of Disaster Risk Reduction*. Elsevier, 14, pp. 37–45. doi: 10.1016/j.ijdrr.2014.11.011.

Paton, D. and Johnston, D. (2001) 'Disasters and communities: Vulnerability, resilience and preparedness', *Disaster Prevention and Management: An International Journal*, 10(4), pp. 270–277. doi: 10.1108/EUM0000000005930.

Patt, A. and Dessai, S. (2005) 'Communicating uncertainty: Lessons learned and suggestions for climate change assessment', *Comptes Rendus - Geoscience*, 337(4), pp. 425–441. doi: 10.1016/j.crte.2004.10.004.

Pennebaker, J. W. and Harber, K. D. (1993) 'A Social Stage Model of Collective Coping: The Loma Prieta Earthquake and The Persian Gulf War', *Journal of Social Issues*, 49(4), pp. 125–145. doi: 10.1111/j.1540-4560.1993.tb01184.x.

Peresan, A., Kossobokov, V. G. and Panza, G. F. (2012) 'Operational earthquake forecast/prediction', *Rendiconti Lincei*, 23(2), pp. 131–138. doi: 10.1007/s12210-012-0171-7.

Perez-Fuentes, G., Verrucci, E. and Joffe, H. (2016) 'A review of current earthquake and fire preparedness campaigns: What works?', in Kotsireas, I. S., Nagurney, A., and Panos, P. M. (eds) *Dynamics of Disasters—Key Concepts, Models, Algorithms, and Insights*. Springer International Publishing, pp. 257–267.

Perry, R. and Lindell, M. K. (1990) 'Predicting long - term adjustment to volcano hazard', *International Journal of Mass Emergencies and Disasters*, pp. 117–36.

Perry, S. C. *et al.* (2016a) *Get your science used—Six guidelines to improve your products*, *Circular*. Reston, VA. doi: 10.3133/cir1419.

Perry, S. C. *et al.* (2016b) *Get your science used—Six guidelines to improve your products*, *Circular*. Reston, VA. doi: 10.3133/cir1419.

Persoskie, A. and Downs, J. S. (2015) 'Experimental Tests of Risk Ladders in the Elicitation of Perceived Likelihood', *Journal of Behavioral Decision Making*, 28(5), pp. 424–436. doi: 10.1002/bdm.1858.

Peter, C. and Koch, T. (2016) 'When Debunking Scientific Myths Fails (and When It Does Not): The Backfire Effect in the Context of Journalistic Coverage and Immediate Judgments as Prevention Strategy', *Science Communication*, 38(1), pp. 3–25. doi: 10.1177/1075547015613523.

Peters, E. (2008) 'Numeracy and the perception and communication of risk', *Annals of the New York Academy of Sciences*, 1128, pp. 1–7. doi: 10.1196/annals.1399.001.

Peters, E. and Slovic, P. (1996) 'The Role of Affect and Worldviews as Orienting Dispositions in the Perception and Acceptance of Nuclear Power', *Journal of Applied Social Psychology*, 26(16), pp. 1427–1453. doi: 10.1111/j.1559-1816.1996.tb00079.x.

Peters, E. and Slovic, P. (2000) 'The springs of action: Affective and analytical information processing in choice', *Personality and Social Psychology Bulletin*, 26(12), pp. 1465–1475. doi: 10.1177/01461672002612002.

Petersen, M. P. (2007) 'Elements of multimedia cartography', in *Multimedia Cartography*. Springer Verlag Heidelberg, pp. 63–73.

Pfau, M. *et al.* (2001) 'The effects of party- and PAC-sponsored issue advertising and the potential of inoculation to combat its impact on the democratic process', *American Behavioral Scientist*, 44(12), pp. 2379–2397. doi: 10.1177/00027640121958384.

Pidgeon, N., Kasperson, R. and Slovic, P. (2003) *The Social Amplification of Risk*. Cambridge: Cambridge University Press. doi: 10.1017/CBO9780511550461.

Pinker, S. (1990) 'A theory of graph comprehension.', in *Artificial intelligence and the future of testing.* Hillsdale, NJ, US: Lawrence Erlbaum Associates, Inc, pp. 73–126.

Poland, G. A. and Spier, R. (2010) 'Fear, misinformation, and innumerates: How the Wakefield paper, the press, and advocacy groups damaged the public health', *Vaccine*, 28(12), pp. 2361–2362. doi: 10.1016/j.vaccine.2010.02.052.

Potter, S. H. *et al.* (2018) 'The influence of impact-based severe weather warnings on risk perceptions and intended protective actions', *International Journal of Disaster Risk Reduction*. Elsevier Ltd, 30(March), pp. 34–43. doi: 10.1016/j.ijdrr.2018.03.031.

Powell, S. W. and O'Hair, D. H. (2008) 'Communicating Weather Information to the Public: People's Reactions and Understandings of Weather Information and Terminology', *Third Symposium on Policy and Socio-Economic Research*, (January 2008), p. P 1.3.

Puttick, R. (2018) *Useful Evidence Mapping the Standards of Evidence used in UK social policy*. Available at: https://www.alliance4usefulevidence.org/assets/2018/05/Mapping-Standards-of-Evidence-A4UE-final.pdf.

Qin, S. *et al.* (2009) 'Acute Psychological Stress Reduces Working Memory-Related Activity in the

Dorsolateral Prefrontal Cortex', *Biological Psychiatry*. Society of Biological Psychiatry, 66(1), pp. 25–32. doi: 10.1016/j.biopsych.2009.03.006.

Rabinovich, A. and Morton, T. A. (2012) 'Unquestioned answers or unanswered questions: Beliefs about science guide responses to uncertainty in climate change risk communication', *Risk Analysis*. Rabinovich, Anna, University of Exeter, School of Psychology, Perry Road, EX4 4QG, Exeter, United Kingdom: Wiley-Blackwell Publishing Ltd., 32(6), pp. 992–1002. doi: 10.1111/j.1539-6924.2012.01771.x.

Rappaport, E. N. (2000) 'Loss of life in the United States associated with recent atlantic tropical cyclones', *Bulletin of the American Meteorological Society*, 81(9), pp. 2065–2073. doi: 10.1175/1520-0477(2000)081<2065:LOLITU>2.3.CO;2.

Ratwani, R. M. and Trafton, J. G. (2008) 'Shedding light on the graph schema: Perceptual features versus invariant structure', *Psychonomic Bulletin and Review*, 15(4), pp. 757–762. doi: 10.3758/PBR.15.4.757.

Red Cross Red Crescent and UK Met Office (2018) *IBF: Impact-based forecasting*. Available at: https://www.510.global/impact-based-forecast/.

Renn, O. *et al.* (1992) 'Social amplification theory: Theoretical foundations and empirical applications', *Journal of Social Issues*, 48(4), pp. 127–160.

Renn, O. (2008) 'Chapter 1 White Paper on Risk Governance : Toward an Integrative Framework 1 Purpose and Objectives of This White Paper', *Governance An International Journal Of Policy And Administration*, (1), pp. 3–73.

Renn, O. (2011) 'The social amplification/attenuation of risk framework: Application to climate change', *Wiley Interdisciplinary Reviews: Climate Change*, 2(2), pp. 154–169. doi: 10.1002/wcc.99.

Ricchetti-Masterson, K. and Horney, J. (2013) 'Social Factors as Modifiers of Hurricane Irene Evacuation Behavior in Beaufort County, NC', *PLoS Currents*, (JUNE). doi: 10.1371/currents.dis.620b6c2ec4408c217788bb1c091ef919.

Richard Eiser, J. *et al.* (2012) 'Risk interpretation and action: A conceptual framework for responses to natural hazards', *International Journal of Disaster Risk Reduction*. Elsevier, 1(1), pp. 5–16. doi: 10.1016/j.ijdrr.2012.05.002.

Riley, S. (2007) 'Large-Scale Models of Infectious Disease', *Science*, 316(June), pp. 1298–1301. Available at: http://www.sciencemag.org/content/316/5829/1298.abstract.

Ripberger, J. T., Silva, C. L., Jenkins-Smith, H. C., Carlson, D. E., *et al.* (2015) 'False Alarms and Missed Events: The Impact and Origins of Perceived Inaccuracy in Tornado Warning Systems', *Risk Analysis*, 35(1), pp. 44–56. doi: 10.1111/risa.12262.

Ripberger, J. T., Silva, C. L., Jenkins-Smith, H. C. and James, M. (2015) 'The influence of consequence-based messages on public responses to tornado warnings', *Bulletin of the American Meteorological Society*, 96(4), pp. 577–590. doi: 10.1175/BAMS-D-13-00213.1.

Ripberger, J. T. *et al.* (2019) 'Measuring Tornado Warning Reception, Comprehension, and Response in the United States', *Weather, Climate, and Society*, 11(4), pp. 863–880. doi: 10.1175/wcas-d-19-0015.1.

Robinson, A. H. *et al.* (1995) *Elements of cartography*. 4th edn. New York: John Wiley & Sons.

Robinson, S. E., Pudlo, J. M. and Wehde, W. (2019) 'The New Ecology of Tornado Warning Information: A Natural Experiment Assessing Threat Intensity and Citizen-to-Citizen Information Sharing', *Public Administration Review*, 79(6), pp. 905–916. doi: 10.1111/puar.13030.

Roeloffs, E. A. and Goltz, J. D. (2017) 'The California Earthquake Advisory Plan: A history', *Seismological Research Letters*, 88(3), pp. 784–797. doi: 10.1785/0220160183.

Rogers, R. D. (1975) 'A protection motivation theory of fear appeals and attitude change', *The Journal of Psychology*, pp. 93–114.

Roozenbeek, J. *et al.* (2020) 'Susceptibility to misinformation about COVID-19 around the world', *Royal Society Open Science*, 7(10), p. 201199. doi: 10.1098/rsos.201199.

Roozenbeek, J. and van der Linden, S. (2019a) 'Fake news game confers psychological resistance against online misinformation', *Palgrave Communications*, 5(65). doi: 10.1057/s41599-019-0279-9.

Roozenbeek, J. and van der Linden, S. (2019b) 'The fake news game: actively inoculating against the risk of misinformation', *Journal of Risk Research*. Routledge, 22(5), pp. 570–580. doi: 10.1080/13669877.2018.1443491.

Rosa, E. A. (2003) *The logical structure of the social amplification of risk framework (SARF): Metatheoretical foundations and policy implications*, *The Social Amplification of Risk*. doi: 10.1017/CBO9780511550461.003.

Roth, E. *et al.* (1990) 'What do we know about making risk comparisons?', *Risk Analysis*, 10(3), pp. 375–387. doi: 10.1111/j.1539-6924.1990.tb00520.x.

Rottenstreich, Y. and Hsee, C. K. (2001) 'Money, kisses, and electric shocks: On the Affective Psychology of Risk', *Psychological Science*, 12(3), pp. 185–190. doi: 10.1111/1467-9280.00334.

Roulston, M. S. *et al.* (2006) 'A laboratory study of the benefits of including uncertainty information in weather forecasts', *Weather and Forecasting*, 21(1), pp. 116–122. doi: 10.1175/WAF887.1.

Ruginski, I. T. *et al.* (2016) 'Non-expert interpretations of hurricane forecast uncertainty visualizations', *Spatial Cognition and Computation*, 16(2), pp. 154–172. doi: 10.1080/13875868.2015.1137577.

Russell, L. ., Goltz, J. . and Bourque, L. B. (1995) 'Preparedness and Hazard Mitigation Actions Before and After Two Earthquakes', *Environment and Behavior*, 27(6), pp. 744–770.

Sandman, P. M., Weinstein, N. D. and Miller, P. (1994) 'High risk or low: how location on a "risk ladder" affects perceived risk.', *Risk analysis : an official publication of the Society for Risk Analysis*, 14(1), pp. 35–45. Available at: http://www.ncbi.nlm.nih.gov/pubmed/8146401 (Accessed: 17 February 2017).

Santesso, N. *et al.* (2020) 'GRADE guidelines 26: informative statements to communicate the findings of systematic reviews of interventions', *Journal of Clinical Epidemiology*, 119, pp. 126–135. doi: 10.1016/j.jclinepi.2019.10.014.

Savadori, L. *et al.* (2004) 'Expert and public perception of risk from biotechnology', *Risk Analysis*, 24(5), pp. 1289–1299. doi: 10.1111/j.0272-4332.2004.00526.x.

Savelli, S. and Joslyn, S. (2012) 'Boater safety: Communicating weather forecast information to high-stakes end users', *Weather, Climate, and Society*, 4(1), pp. 7–19. doi: 10.1175/WCAS-D-11-00025.1.

Schapira, M. M., Nattinger, A. B. and McHorney, C. A. (2001) 'Frequency or probability? A qualitative study of risk communication formats used in health care', *Medical Decision Making*, 21(6), pp. 459–467. doi: 10.1177/0272989X0102100604.

Schapira, M. M., Nattinger, A. B. and McHorney, C. A. (2015) 'Frequency or probability? A qualitative study of risk communication formats used in health care.', *Medical decision making : an international journal of the Society for Medical Decision Making*, 21(6), pp. 459–467. doi: 10.1177/0272989X0102100604.

Schneider, C. R., Freeman, A. L. J. and van der Linden, S. L. (2021) 'The effects of quality of evidence communication on trust and decision making in the context of COVID-19: loss aversion and ambiguity avoidance', *under review*.

Schneider, S. H. (2002) 'Keeping out of the box', *American Scientist*, 90(Nov-Dec), pp. 496–498.

Schultz, D. M. *et al.* (2010) 'Decision Making by Austin, Texas, Residents in Hypothetical Tornado Scenarios*', *Weather, Climate, and Society*, 2(3), pp. 249–254. doi: 10.1175/2010WCAS1067.1.

Schwarz, N., Newman, E. and Leach, W. (2016) 'Making the truth stick & the myths fade: Lessons from cognitive psychology', *Behavioural Science & Policy*, 2(1), pp. 85–95. Available at:

http://media.proquest.com.ezproxy.library.wisc.edu/media/pq/classic/doc/763763431/fmt/pi/rep/NONE?hl=cognitions%2Ccognition%2Ccognitions%2Ccognition&cit%3Aauth=Bradfield%2C+Ron&cit%3Atitle=What+We+Know+and+What+We+Believe%3A+Lessons+from+cognitive+psychol.

Scolobig, A., De Marchi, B. and Borga, M. (2012) 'The missing link between flood risk awareness and preparedness: Findings from case studies in an Alpine Region', *Natural Hazards*, 63(2), pp. 499–520. doi: 10.1007/s11069-012-0161-1.

Seeger, M. W. (2006) 'Best practices in crisis communication: An expert panel process', *Journal of Applied Communication Research*, 34(3), pp. 232–244. doi: 10.1080/00909880600769944.

Sellnow, D. D., Iverson, J. and Sellnow, T. L. (2017) 'The evolution of the operational earthquake forecasting community of practice: the L'Aquila communication crisis as a triggering event for organizational renewal', *Journal of Applied Communication Research*. Taylor & Francis, 45(2), pp. 121–139. doi: 10.1080/00909882.2017.1288295.

Senkbeil, J. C., Rockman, M. S. and Mason, J. B. (2012) 'Shelter seeking plans of tuscaloosa residents for a future tornado event', 4(3), pp. 159–171. doi: 10.1175/WCAS-D-11-00048.1.

Severtson, D. J. and Vatovec, C. (2012) 'The Theory-Based Influence of Map Features on Risk Beliefs: Self-Reports of What Is Seen and Understood for Maps Depicting an Environmental Health Hazard', *Journal of Health Communication*. Taylor & Francis, 17(7), pp. 836–856. doi: 10.1080/10810730.2011.650933.

Sharot, T. (2011) 'The optimism bias', *Current Biology*. Elsevier, 21(23), pp. R941–R945. doi: 10.1016/j.cub.2011.10.030.

Shenhar, G. *et al.* (2015) 'The Impact of a National Earthquake Campaign on Public Preparedness: 2011 Campaign in Israel as a Case Study', *Disaster Medicine and Public Health Preparedness*. Cambridge University Press, 9(2), pp. 138–144. doi: 10.1017/dmp.2014.58.

Sherman-Morris, K. (2010) 'Tornado warning dissemination and response at a university campus', *Natural Hazards*, 52(3), pp. 623–638. doi: 10.1007/s11069-009-9405-0.

Shiffrin, R. M. and Nosofsky, R. M. (1994) 'Seven plus or minus two: A commentary on capacity limitations.', *Psychological Review*, pp. 357–361. doi: 10.1037//0033-295x.101.2.357.

Siegrist, M. (1997) 'Communicating low risk magnitudes: Incidence rates expressed as frequency versus rates expressed as probability', *Risk Analysis*, 17(4), pp. 507–510. doi: 10.1111/j.1539-6924.1997.tb00891.x.

Siegrist, M. and Cvetkovich, G. (2000) 'Perception of hazards: The role of social trust and knowledge', *Risk Analysis*, 20(5), pp. 713–720. doi: 10.1111/0272-4332.205064.

Siegrist, M., Orlow, P. and Keller, C. (2008) 'The effect of graphical and numerical presentation of hypothetical prenatal diagnosis results on risk perception', *Medical Decision Making*, 28(4), pp. 567–574. doi: 10.1177/0272989X08315237.

Siegrist, M. and Zingg, A. (2014) 'The role of public trust during pandemics: Implications for crisis communication.', *European Psychologist*, 19(1), pp. 23–32.

Simmons, K. M. and Sutter, D. (2008) 'Tornado warnings, lead times, and tornado casualties: An empirical investigation', *Weather and Forecasting*, 23(2), pp. 246–258. doi: 10.1175/2007WAF2006027.1.

Simmons, K. M. and Sutter, D. (2009) 'False alarms, tornado warnings, and tornado casualties', *Weather, Climate, and Society*, 1(1), pp. 38–53. doi: 10.1175/2009WCAS1005.1.

Sisco, M. R. *et al.* (2020) 'A Finite Pool of Worry or a Finite Pool of Attention? Evidence and Qualifications Matthew', *preprint*.

Sivle, A. D. *et al.* (2014) 'How do laypeople evaluate the degree of certainty in a weather report? A case study of the use of the web service yr.no', *Weather, Climate, and Society*, 6(3), pp. 399–412. doi: 10.1175/WCAS-D-12-00054.1.

Sjöberg, L. (2000) ‘Factors in risk perception’, *Risk Analysis*. doi: 10.1111/0272-4332.00001.

Slocum, T. A. *et al.* (2004) ‘A qualitative evaluation of maptime, a program for exploring spatiotemporal point data’, *Cartographica*, 39(3), pp. 43–68. doi: 10.3138/92T3-T928-8105-88X7.

Slovic, P. (1992) ‘Perception of Risk: Reflections on the Psychometric Paradigm’, *Social Theories of Risk*, pp. 117–152. Available at: https://scholarsbank.uoregon.edu/xmlui/bitstream/handle/1794/22510/slovic_289.pdf?sequence=1.

Slovic, P. (1993) ‘Perceived Risk, Trust, and Democracy’, *Risk Analysis*, 13(6), pp. 675–682. doi: 10.1111/j.1539-6924.1993.tb01329.x.

Slovic, P. (1999) ‘Trust, Emotion, Sex, Politics, and Science: Surveying the Risk-Assessment Battlefield’, 19(4), pp. 689–701.

Slovic, P. (2000) *The perception of risk.*, *The perception of risk.* Edited by P. Slovic. London, England: Earthscan Publications (Risk, society, and policy series.).

Slovic, P. *et al.* (2004) ‘Risk as Analysis and Risk as Feelings: Some Thoughts about Affect, Reason, Risk, and Rationality’, *Risk Analysis*. doi: 10.1111/j.0272-4332.2004.00433.x.

Slovic, P. *et al.* (2007) ‘The affect heuristic’, *European Journal of Operational Research*, 177(3), pp. 1333–1352. doi: 10.1016/j.ejor.2005.04.006.

Slovic, P., Fischhoff, B. and Lichtenstein, S. (1978) ‘Accident probabilities and seat belt usage: A psychological perspective’, *Accident Analysis and Prevention*, 10(4), pp. 281–285. doi: 10.1016/0001-4575(78)90030-1.

Slovic, P., Fischhoff, B. and Lichtenstein, S. (1981) ‘Perceived risk: psychological factors and social implications’, *Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences*, 376(1764), pp. 17–34. doi: 10.1098/rspa.1981.0073.

Slovic, P., Fischhoff, B. and Lichtenstein, S. (1982) ‘Why Study Risk Perception?’, *Risk Analysis*, 2(2), pp. 83–93. doi: 10.1111/j.1539-6924.1982.tb01369.x.

Slovic, P., Kraus, N. and Covello, V. T. (1990) ‘What Should We Know About Making Risk Comparisons?’, *Risk Analysis*, 10(3), pp. 389–392. doi: 10.1111/j.1539-6924.1990.tb00521.x.

Slovic, P., Monahan, J. and MacGregor, D. G. (2000) ‘Violence risk assessment and risk communication: The effects of using actual cases, providing instructions, and employing probability vs. frequency formats’, *Law & Human Behavior*, 24(3), pp. 271–296. doi: 10.1023/A:1005595519944.

Smerecnik, C. M. R. *et al.* (2010) ‘Understanding the positive effects of graphical risk information on comprehension: Measuring attention directed to written, tabular, and graphical risk information’, *Risk Analysis*, 30(9), pp. 1387–1398. doi: 10.1111/j.1539-6924.2010.01435.x.

Smith, D. I. (2000) ‘Floodplain management: problems, issues and opportunities’, in Parker, D. J. (ed.) *Floods, vol 1*. London: Routledge, pp. 254–267.

Smith, N. and Joffe, H. (2013) ‘How the public engages with global warming: A social representations approach’, *Public Understanding of Science*, 22(1), pp. 16–32. doi: 10.1177/0963662512440913.

Smith, N. and Leiserowitz, A. (2012) ‘The Rise of Global Warming Skepticism: Exploring Affective Image Associations in the United States Over Time’, *Risk Analysis*, 32(6), pp. 1021–1032. doi: 10.1111/j.1539-6924.2012.01801.x.

Solberg, C., Rossetto, T. and Joffe, H. (2010) ‘The social psychology of seismic hazard adjustment: Re-evaluating the international literature’, *Natural Hazards and Earth System Science*, 10(8), pp. 1663–1677. doi: 10.5194/nhess-10-1663-2010.

Sorensen, J. H. and Mileti, D. S. (1987) ‘Programs that encourage the adoption of precautions against natural hazards: review and evaluation’, in Weinstein, N. D. E. (ed.) *Taking Care: Understanding and Encouraging Self-Protective Behavior*. Cambridge University Press, pp. 208–230. doi: 10.1017/CBO9780511527760.013.

Spiegelhalter, D. J. (2017) ‘Risk and Uncertainty Communication’, *Annual Review of Statistics and Its Application*, 4(1), pp. 31–60. doi: 10.1146/annurev-statistics-010814-020148.

Spiegelhalter, D. J., Pearson, M. and Short, I. (2011) ‘Visualizing Uncertainty About the Future’, *Science*, 333(6048), pp. 1393–1400. doi: 10.1126/science.1191181.

Starr, C. (1969) ‘Social Benefit Versus Technological Risk: What is Our Society Willing to Pay for Safety?’, *Renewable Energy*, 165, pp. 136–152. doi: 10.4324/9781315793245-125.

Steelman, T. A. *et al.* (2015) ‘What information do people use, trust, and find useful during a disaster? Evidence from five large wildfires’, *Natural Hazards*, 76(1), pp. 615–634. doi: 10.1007/s11069-014-1512-x.

Stefánsson, R., Guðmundsson, G. B. and Halldórsson, P. (2000) *The two large earthquakes in the South Iceland seismic zone on June 17 and 21, 2000*, *Iceland Meteorological Office*. Available at: http://hraun.vedur.is/ja/skyrslur/June17and21_2000/index.html.

Stehle, S. and Kitchin, R. (2020) ‘Real-time and archival data visualisation techniques in city dashboards’, *International Journal of Geographical Information Science*. Taylor & Francis, 34(2), pp. 344–366. doi: 10.1080/13658816.2019.1594823.

Stewart, I. S., Ickert, J. and Lacassin, R. (2018) ‘Communicating Seismic Risk: the Geoethical Challenges of a People-Centred, Participatory Approach’, *Annals of GeophysicsAnnals of Geophysics*, 60. doi: 10.4401/ag-7593.

Steynor, A. *et al.* (2016) ‘Co-exploratory climate risk workshops: Experiences from urban Africa’, *Climate Risk Management*. The Authors, 13, pp. 95–102. doi: 10.1016/j.crm.2016.03.001.

van Stiphout, T., Wiemer, S. and Marzocchi, W. (2010) ‘Are short-term evacuations warranted? Case of the 2009 L’Aquila earthquake’, *Geophysical Research Letters*, 37(6), pp. 1–5. doi: 10.1029/2009gl042352.

Stone, E. R., Yates, J. F. and Parker, A. M. (1994) ‘Risk communication: Absolute versus relative expressions of low-probability risks’, *Organizational Behavior and Human Decision Processes*, pp. 387–408. doi: 10.1006/obhd.1994.1091.

Takayasu, M. *et al.* (2015) ‘Rumor diffusion and convergence during the 3.11 Earthquake: A twitter case study’, *PLoS ONE*, 10(4), pp. 1–18. doi: 10.1371/journal.pone.0121443.

Tan, M. L. *et al.* (2020) ‘Understanding end-users’ perspectives: Towards developing usability guidelines for disaster apps’, *Progress in Disaster Science*. The Authors, 7, p. 100118. doi: 10.1016/j.pdisas.2020.100118.

Tanaka, K. (2005) ‘The impact of disaster education on public preparation and mitigation for earthquakes: A cross-country comparison between Fukui, Japan and the San Francisco Bay Area, California, USA’, *Applied Geography*, 25(3), pp. 201–225. doi: 10.1016/j.apgeog.2005.07.001.

Terpstra, T., Lindell, M. K. and Gutteling, J. M. (2009) ‘Does communicating (flood) risk affect (flood) risk perceptions? results of a quasi-experimental study’, *Risk Analysis*, 29(8), pp. 1141–1155. doi: 10.1111/j.1539-6924.2009.01252.x.

Thakur, S. and Hanson, A. J. (2010) ‘A 3D visualization of multiple time series on maps’, *Proceedings of the International Conference on Information Visualisation*, pp. 336–343. doi: 10.1109/IV.2010.54.

The Atlantic (2010) *Does Gay Sex Cause Earthquakes?* Available at: https://www.theatlantic.com/international/archive/2010/02/does-gay-sex-cause-earthquakes/36039/ (Accessed: 16 November 2020).

The Guardian (2015) *Earthquakes caused by nudity, short skirts, gay marriage and other scapegoats*. Available at: https://www.theguardian.com/world/shortcuts/2015/jun/10/earthquakes-caused-by-nudity-short-skirts-gay-marriage-and-other-scapegoats (Accessed: 16 November 2020).

The Independent (2016) *Gay sex causes earthquakes and ‘disgusts’ Allah, says Muslim cleric in Ghana*. Available at: https://www.independent.co.uk/news/world/africa/gay-sex-causes-earthquakes-and-disgusts-allah-says-muslim-cleric-ghana-a7051336.html (Accessed: 16 November 2020).

Thompson, M. A., Lindsay, J. M. and Gaillard, J. C. (2015) 'The influence of probabilistic volcanic hazard map properties on hazard communication', *Journal of Applied Volcanology*, 4(1). doi: 10.1186/s13617-015-0023-0.

Tierney, K., Lindell, M. K. and Perry, R. W. (2001) *Facing the Unexpected : Disaster Preparedness and Response in the United States*. Washington, DC, DC: Joseph Henry Press.

Tufte, E. (2001) *The Visual Display of Quantitative Information*. Cheshire, CT, CT: Graphics Press.

Turner, R., Nigg, J. and Paz, D. (1986) *Waiting for disaster: Earthquake watch in California*. Berkeley: University of California Press.

Tversky, A. and Kahneman, D. (1973) 'Availability: A heuristic for judging frequency and probability', *Cognitive Psychology*, 5(2), pp. 207–232. doi: 10.1016/0010-0285(73)90033-9.

Tversky, A. and Kahneman, D. (1974a) 'Judgment under uncertainty: Heuristics and biases', *Science*, 185(4157), pp. 1124–1131. doi: 10.4324/9781912282562.

Tversky, A. and Kahneman, D. (1974b) 'Judgment under Uncertainty: Heuristics and Biases', *Science*, 185(4157), pp. 1124–1131.

Tversky, A. and Kahneman, D. (1981) 'The Framing of Decisions and the Psychology of Choice', *Science*, 211(4481), pp. 453–458. Available at: papers2://publication/uuid/82602C0D-4B0E-46E3-8627-ED158AE8CED9.

Tversky, A. and Kahneman, D. (1991) 'Loss Aversion in Riskless Choice : A Reference-Dependent Model', 106(4), pp. 1039–1061.

Tversky, B., Morrison, J. B. and Betrancourt, M. (2002) 'Animation: can it facilitate? The enthusiasm for graphics of all kinds rests on the belief that they benefit comprehension and learning, and foster insight (their proponents include Levie', *Int. J. Human-Computer Studies Schnotz & Kulhavy*, 57, pp. 247–262. doi: 10.1006/ijhc.1017.

Vaughan, C. *et al.* (2016) 'Identifying research priorities to advance climate services', *Climate Services*. The Authors, 4, pp. 65–74. doi: 10.1016/j.cliser.2016.11.004.

Vaughan, C., Dessai, S. and Hewitt, C. (2018) 'Surveying climate services: What can we learn from a bird's-eye view?', *Weather, Climate, and Society*, 10(2), pp. 373–395. doi: 10.1175/WCAS-D-17-0030.1.

Vickers, P. (2011) 'Sonification for Process Monitoring', in Hermann, T., Hunt, A., and Neuhoff, J. G. (eds) *The Sonification Handbook*. Berlin, Germany: Logos Publishing House, pp. 455–492. Available at: http://nrl.northumbria.ac.uk/5532/.

Villeneuve, P. and Mao, Y. (1994) 'Lifetime probability of developing lung cancer, by smoking status, Canada', *Can J Public Health*, 85(6), pp. 385–8.

Visschers, V. H. M. M. *et al.* (2009) 'Probability information in risk communication: A review of the research literature', *Risk Analysis*, 29(2), pp. 267–287. doi: 10.1111/j.1539-6924.2008.01137.x.

Volpini, A. (2009) *L'Ospedale nel Sistema dei Soccorsi Sanitari*. Rome.

Van Vugt, M., Griskevicius, V. and Schultz, P. W. (2014) 'Naturally green: Harnessing stone age psychological biases to foster environmental behavior', *Social Issues and Policy Review*, 8(1), pp. 1–32. doi: 10.1111/sipr.12000.

Wagner, K. (2004) *Naturgefahrenbewusstsein und -kommunikation am Beispiel von Sturzfluten und Rutschungen in vier Gemeinden des bayerischen Alpenraums*. München, Germany.

Wald, D. *et al.* (2008) 'ShakeCast: Automating and improving the use of shakemap for post-earthquake deeision-making and response', *Earthquake Spectra*, 24(2), pp. 533–553. doi: 10.1193/1.2923924.

Wald, D. J. *et al.* (1999) 'TriNet "ShakeMaps": Rapid Generation of Peak Ground Motion and Intensity Maps for Earthquakes in Southern California', *Earthquake Spectra*. SAGE Publications Ltd STM, 15(3), pp. 537–555. doi: 10.1193/1.1586057.

Wald, D. J. *et al.* (2006) *ShakeMap Manual: Technical Manual, User's Guide, and Software Guide*, *USGS*. Available at: https://pubs.usgs.gov/tm/2005/12A01/pdf/508TM12-A1.pdf%0Ahttp://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:ShakeMap+Manual#1.

Walter, N. and Tukachinsky, R. (2020) 'A Meta-Analytic Examination of the Continued Influence of Misinformation in the Face of Correction: How Powerful Is It, Why Does It Happen, and How to Stop It?', *Communication Research*, 47(2), pp. 155–177. doi: 10.1177/0093650219854600.

Wang, K. and Rogers, G. C. (2014) 'Earthquake preparedness should not fluctuate on a daily or weekly basis', *Seismological Research Letters*, 85(3), pp. 569–571. doi: 10.1785/0220130195.

Ware, C. (2013) *Information Visualization: Perception for Design*. Third Edit. Morgan Kaufman. Available at: http://repository.fue.edu.eg/xmlui/bitstream/handle/123456789/3549/8172.pdf?sequence=1&isAllowed=y.

Weber, E. U. and Hilton, D. J. (1990) 'Contextual Effects in the Interpretations of Probability Words: Perceived Base Rate and Severity of Events', *Journal of Experimental Psychology: Human Perception and Performance*, 16(4), pp. 781–789. doi: 10.1037/0096-1523.16.4.781.

Wein, A. *et al.* (2016) 'Communicating with the public during an earthquake sequence: Improving communication of geoscience', *Seismological Research Letters*, 87(1), pp. 112–118. doi: 10.1785/0220150113.

Wein, A. and Becker, J. (2013) 'Communicating aftershock risk: Roles for reassuring the public', *Risk Frontiers Newsletter*, 13(3), pp. 3–4.

Weinstein, N. D. and Sandman, P. M. (1993) 'Some criteria for evaluating risk messages', *Risk Analysis*. Blackwell Publishing Ltd, 13(1), pp. 103–114. doi: 10.1111/j.1539-6924.1993.tb00733.x.

Wertheimer, M. (1923) 'Untersuchungen zur Lehre von der Gestalt II', *Psychologische Forschung*, 4, pp. 301–350.

Whitney, D. J., Lindell, M. K. and Nguyen, H. D. (2004) 'Earthquake beliefs and adoption of seismic hazard adjustments', *Risk Analysis*, 24(1), pp. 87–102.

Wikipedia (2020) *Brier score*, *Wikipedia*. Available at: https://en.wikipedia.org/wiki/Brier_score (Accessed: 26 November 2020).

Wilson, R. and Crouch, E. A. C. (1987) 'Risk Assessment and Comparisons: An Introduction', *Science*, 236.

Windschitl, P. D. and Weber, E. U. (1999) 'The Interpretation of "Likely" Depends on the Context, but "70%" Is 70%—Right? The Influence of Associative Processes on Perceived Certainty', *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 25(6), pp. 1514–1533. Available at: http://psycnet.apa.org/fulltext/1999-01477-010.pdf.

Windschitl, P. D. and Wells, G. L. (1996) 'Measuring Psychological Uncertainty: Verbal Versus Numeric Methods', *Journal of Experimental Psychology: Applied*, 2(4), pp. 343–364. doi: 10.1037/1076-898X.2.4.343.

Witteman, C. and Renooij, S. (2003) 'Evaluation of a verbal-numerical probability scale', *International Journal of Approximate Reasoning*, 33(2), pp. 117–131. doi: 10.1016/S0888-613X(02)00151-2.

Woo, G. and Marzocchi, W. (2014) 'Operational Earthquake Forecasting and Decision-Making', pp. 353–367. doi: 10.1007/978-3-642-12233-0_18.

Wood, M. D. *et al.* (2012) 'Cognitive Mapping Tools: Review and Risk Management Needs', *Risk Analysis*, 32(8), pp. 1333–1348. doi: 10.1111/j.1539-6924.2011.01767.x.

Wood, M. M. (2013) *Engaging Californians in a Shared Vision for Resiliency: Practical Lessons*

Learned from the Great California Shakeout.

World Economic Forum (2014) *Outlook on the Global Agenda*. Available at: http://reports.weforum.org/outlook-14/.

World Meteorological Organization (2008) 'Guidelines on communicating forecast uncertainty', *Wmo Td-1722*, PWS-18, p. 25 pages. Available at: https://www.wmo.int/pages/prog/amp/pwsp/documents/TD-1422.pdf.

World Meteorological Organization (2015) *WMO Guidelines on Multi-hazard Impact-based Forecast and Warning Services*.

Wright, W. (1995) 'Information animation applications in the capital markets', *Proceedings of the Information Visualization Conference*, pp. 19–25.

Xue, W. *et al.* (2014) 'Cultural worldviews and environmental risk perceptions: Ameta-analysis', *Journal of Environmental Psychology*. Elsevier Ltd, 40, pp. 249–258. doi: 10.1016/j.jenvp.2014.07.002.

Yamagishi, K. (1997) 'When a 12.86 % Mortality is More Dangerous than 24.14 %: Implications for Risk Communication', *Applied Cognitive Psychology*, 11(January), pp. 495–506. doi: 10.1002/(SICI)1099-0720(199712)11:6<495::AID-ACP481>3.0.CO;2-J.

Zabini, F. *et al.* (2015) 'Communication and interpretation of regional weather forecasts: A survey of the Italian public', *Meteorological Applications*, 22(3), pp. 495–504. doi: 10.1002/met.1480.

Zender, M. (2006) 'Advancing Icon Design for Global Non Verbal Communication: Or What Does the Word Bow Mean?', *Visible Language*, 40(2), p. 178.