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Perception and Use of Uncertainty in Severe Weather Warnings

by

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List of Acronyms

ANOVA	analysis of variance
BMVI	Federal Ministry of Transport and Digital Infrastructures
CI	confidence interval
DRK	German Red Cross
DWD	Deutscher Wetterdienst
EPS	Ensemble-Prediction-Systems
FeWIS	Feuerwehr-Wetterinformationssystem
FwD100	Feuerwehr Dienstvorschrift 100
HErZ	Hans-Ertel-Centre for Weather Research
NHMS	national hydro-meteorological service
NOAA	National Oceanic and Atmospheric Administration
NWP	numerical weather prediction
SERA	Societal and Economic Applications
SD	standard deviation
THW	Federal Agency for Technical Relief
THORPEX	The Observing System Research and Predictability Experiment
TV	television
UNISDR	United Nations International Strategy for Disaster Reduction
UK	United Kingdom
US	United States of America
WAS*IS	Weather and Society * Integrated Studies
WEXICOM	Wetterwarnungen: Von der Extremereignis-Information zu Kommunikation und Handlung
WMO	World Meteorological Organisation
WWRP	World Weather Research Programme

Abstract

Uncertainty is an essential part of atmospheric processes and thus inherent to weather forecasts. Nevertheless, weather forecasts and warnings are still predominately issued as deterministic (yes or no) forecasts, although research suggests that providing weather forecast users with additional information about the forecast uncertainty can enhance the preparation of mitigation measures. Communicating forecast uncertainty would allow for a provision of information on possible future events at an earlier time. The desired benefit is to enable the users to start with preparatory protective action at an earlier stage of time based on the their own risk assessment and decision threshold. But not all users have the same threshold for taking action. In the course of the project WEXICOM ('*Wetterwarnungen: Von der Extremereignis-Information zu Kommunikation und Handlung*') funded by the Deutscher Wetterdienst (DWD), three studies were conducted between the years 2012 and 2016 to reveal how weather forecasts and warnings are reflected in weather-related decision-making. The studies asked which factors influence the perception of forecasts and the decision to take protective action and how forecast users make sense of probabilistic information and the additional lead time. In a first exploratory study conducted in 2012, members of emergency services in Germany were asked questions about how weather warnings are communicated to professional end-users in the emergency community and how the warnings are converted into mitigation measures. A large number of open questions were selected to identify new topics of interest. The questions covered topics like users' confidence in forecasts, their understanding of probabilistic information as well as their lead time and decision thresholds to start with preparatory mitigation measures. Results show that emergency service personnel generally have a good sense of uncertainty inherent in weather forecasts. Although no single probability threshold could be identified for organisations to start with preparatory mitigation measures, it became clear that emergency services tend to avoid forecasts based on low probabilities as a basis for their decisions. Based on this findings, a second study conducted with residents of Berlin in 2014 further investigated the question of decision thresholds. The survey questions related to the topics of the perception of and prior experience with severe weather, trustworthiness of forecasters and confidence in weather forecasts, and socio-demographic and social-economic characteristics. Within the questionnaire a scenario was created to determine individual decision thresholds and see whether subgroups of the sample lead to different thresholds. The results show that people's willingness to act tends to be higher and decision thresholds tend to be lower if the expected weather event is more severe or the property at risk is of higher value. Several influencing factors of risk perception have significant effects such as education, housing status and ability to act, whereas socio-demographic determinants alone are often not sufficient to fully grasp risk perception and protection behaviour. Parallel to the quantitative studies, an interview study was conducted with 27 members of German civil protection between 2012 and 2016. The results show that the latest developments in (numerical) weather forecasting do not necessarily fit the current practice of German emergency services. These practices are mostly carried out on alarms and ground truth in a reactive manner rather than on anticipation based on prognosis or forecasts. As the potential consequences rather than the event characteristics determine protective action, the findings support the call and need for impact-based warnings. Forecasters will rely on impact data and need to learn the users' understanding of impact. Therefore, it is recommended to enhance weather communication not only by improving computer models and observation tools, but also by focusing on the aspects of communication and collaboration. Using information about uncertainty demands awareness about and acceptance of the limits of knowledge, hence, the capabilities of the forecaster to anticipate future developments of the atmosphere and the capabilities of the user to make sense of this information.

Zusammenfassung

Obwohl atmosphärische Prozesse wesentlich durch Unsicherheit gekennzeichnet sind, werden Wettervorhersagen und Warnungen in Deutschland überwiegend noch als deterministische (ja oder nein) Vorhersagen herausgegeben. Dagegen legen jüngere Forschungsergebnisse nahe, dass durch die frühzeitige Bereitstellung von Informationen über die Vorhersageunsicherheit, die Vorbereitung von Vorsorgemaßnahmen verbessert werden kann. Der gewünschte Vorteil bestünde darin, es der Empfängerin und dem Empfänger zu ermöglichen auf Grundlage der eigenen Risikobewertung zu einem möglichen früheren Zeitpunkt mit Schutzmaßnahmen zu beginnen. Offen ist dabei, ob diese mit probabilistischen Wettervorhersagen, der Unsicherheit und den Implikationen durch die zusätzliche Vorlaufzeit umgehen können, wie sich Vorhersagen und Warnungen in wetterbezogenen Entscheidungen widerspiegeln und welche Einflussfaktoren auf die Entscheidung wirken. Im Rahmen des vom Deutschen Wetterdienst (DWD) geförderten Projektes WEXICOM (Wetterwarnungen: Von der Extremereignis-Information zu Kommunikation und Handlung) wurden dazu zwischen den Jahren 2012 und 2016 drei Studien durchgeführt. In einer ersten explorativen Studie wurden Vertreterinnen und Vertreter des deutschen Bevölkerungsschutzes gefragt, wie Wetterwarnungen an sie kommuniziert werden und wie sie diese Informationen in Maßnahmen umsetzten. Die Studie bestand aus mehreren offenen Fragen, um möglichst viele neue Themen zu identifizieren. Thematische Schwerpunkte waren das Vertrauen in Wettervorhersagen, das Verständnis von Wahrscheinlichkeiten und die benötigte Vorlaufzeit für vorbereitende Maßnahmen. Die Ergebnisse zeigen, dass die Befragten im Allgemeinen die Unsicherheit in Wettervorhersagen gut einschätzen. Obwohl kein eindeutiger Wahrscheinlichkeitswert identifiziert werden konnte, bei dem sie mit vorbereitenden Maßnahmen beginnen würden, wurde deutlich, dass Feuerwehren

und Rettungsdienste es vermeiden ihre Entscheidungen auf Grund von Vorhersagen mit niedriger Eintrittswahrscheinlichkeit zu treffen. In einer zweiten Fragebogenstudie wurde das Thema der Schwellenwerte für Entscheidungen mit Bewohnern von Berlin weiter untersucht. Es wurde geprüft, welche mögliche Faktoren die individuellen Wahrscheinlichkeitswerte beeinflussen. Der Fragebogen beinhaltete dafür ein fiktives Entscheidungs-Szenario und weitere Fragen zur Wahrnehmung und vorherigen Erfahrung mit Unwetter, der Einschätzung der Vertrauenswürdigkeit von Forecastern und das Vertrauen in Wettervorhersagen sowie soziodemografische und sozioökonomische Merkmale. Die Ergebnisse zeigen, dass die Handlungsbereitschaft tendenziell höher ist und die Schwellenwerte tendenziell niedriger ausfallen, wenn das erwartete Wetterereignis schwerwiegender ist oder das gefährdete Eigentum einen höheren Wert hat. Mehrere Faktoren beeinflussen die Risikowahrnehmung und den Schwellenwert. Darunter Bildung, Wohnstatus und Selbstwirksamkeitserwartung. Wohingegen soziodemografische Merkmale nicht ausreichen, um Risikowahrnehmung und Schutzverhalten vollständig zu erfassen. Parallel zu den quantitativen Studien wurde eine Interviewstudie mit 27 Vertreterinnen und Vertretern des deutschen Bevölkerungsschutzes durchgeführt. Die Ergebnisse zeigen, dass die technologischen Entwicklungen durch die numerische Wettervorhersage nicht zwangsläufig durch die derzeitige Praxis des deutschen Bevölkerungsschutzes aufgegriffen werden können. Dieser reagiert zumeist auf Grundlage von Alarmen und Bestätigungen durch Lagebilder von Ort, anstatt auf der Grundlage von (Wetter-) Vorhersagen zu arbeiten. Die Ergebnisse zeigen insgesamt, dass letztendlich die Konsequenzen von Wetter und nicht das Wetterereignis an sich die Handlungen prägen. Impact-basierende Warnungen können hier aufgrund der Praxisnähe eine hilfreiche Unterstützung für einige Empfängergruppen darstellen. Für diese Form der Warnung benötigen die Wetterdienste Daten zu den Auswirkungen von Wetter. Notwendig dafür ist eine verbesserte Kommunikation und Zusammenarbeit zwischen Wetterdiensten und professionellen Empfängergruppen. So erlernen die Wetterdienste die Bedeutung von Auswirkungen für den einzelnen Empfänger und unterstützen gleichzeitig das Verständnis von numerischen Wettervorhersagen. Die Kommunikation von Vorhersageunsicherheiten erfordert grundlegend ein Bewusstsein und Verständnis über die Grenzen des Wissens und somit über die Fähigkeiten der Forecaster, zukünftige Entwicklungen der Atmosphäre vorherzusagen und über die Fähigkeiten der Empfängerinnen und Empfänger, diese Informationen zu verstehen und umzusetzen.

1 Introduction

Extreme hydro-meteorological events cause major losses both to lives and properties in a highly developed country such as Germany (GDV, 2016; Kreibich et al., 2014; Munich Re, 1999, 2016; UNISDR, 2015). Adequate warnings can enhance the preparation of mitigation and response measures and reduce or even avoid losses (UNISDR, 2015). Yet, such losses reflect an underlying risk that presents many ongoing challenges with respect to disaster preparedness, warning, and response due to for instance the uncertainty and missing knowledge about when (time), where (location) and with which intensity (magnitude) an potential event might occur. As a result of "*the chaotic character of the atmosphere, coupled with inevitable inadequacies in observations and computer models*" uncertainties with respect to the location and magnitude of severe weather events cannot be avoided. "*Uncertainty is thus a fundamental characteristic of weather*" (NRC, 2006, p. 98) and weather forecasting is "*an instructive case of [...] decision making under regimes of high uncertainty*" (Daipha, 2012, p. 15).

Additionally, the uncertainty about the impact of severe weather events will be relevant for the actions that forecast users[1] take in response to warnings. But formal and informal rules (i.e. on how to prepare for and respond to an event), limited available resources (i.e. material equipment or financial provision), communication obstacles (i.e. receiving warning information), difficulties in understanding the information (i.e. literacy and numeracy), or limited knowledge of how to make use of the information are a few of many further impediments to achieving these aims.

Addressing these challenges requires a interdisciplinary approach integrating both geo-

[1]Meaning both individual and institutional members that factor a weather forecast into their decision-making.

physical processes as well as *"the complex web of culture, economics, and politics, and technological resources and development"* (Tobin and Montz, 2009, p. 521) into disaster risk management.

Still, in spite of long-term experience gained with the existing early warning systems (e.g. Zschau and Küppers, 2003) and emergency response facilities to ensure safety (e.g. Jenki et al., 2014), the issue of an optimal warning with respect to extreme hydro-meteorological events cannot be regarded as solved (NRC, 2010).

While enormous progress has been made in the field of hydro-meteorological forecasting, i.e. the progress of numerical weather prediction (NWP) and hydrological and hydraulic modelling as well as general progress in information technology (Rossa et al., 2011), less has been achieved in transforming such forecasts into warning responses (Demeritt et al., 2010, 2013; Doswell, 2015; Nobert et al., 2010; WMO, 2015).

NWP models are capable of forecasting patterns of the atmosphere with significant quality for up to one week (Walter et al., 2009). Forecasts are made for grid points in a reticular structure covering the whole world, whereas the quality of a forecast is reduced with increasing spatial distance of the grid points.

Since the introduction of NWP in the 1960s and 1970s, the use and reliance on NWP model guidance has become evident in the United States of America (US) and Europe since the late 1990s (Schumann, 2009; Stuart et al., 2006). Based on NWP models, "*forecasting has shifted from the manual production of text-based forecasts to the production of gridded forecast databases through the utilization of graphical software tools, with text and other forecast products derived from these databases*" (Stuart et al., 2006, p. 1). Such forecast procedures are based on Ensemble-Prediction-Systems (EPS), an approach that includes several forecasts and models (instead of one 'deterministic' forecast) to derive probabilities of occurrence for specific weather phenomena (e.g. precipitation, wind, sunshine duration) for forecasts up to several days ahead (Schumann, 2009; Wernli, 2012). For example, the forecast of a storm cell or cyclone track could be represented by a single, hence deterministic, line or by multiple lines (or a cone) that indicate the likely (and probabilistic) range of forecast tracks.

The use of EPS allows a forecaster to make estimates about the uncertainty of weather forecasts by capturing, e.g. the uncertainty of current initial atmospheric conditions to provide quantitative probability forecasts (Wernli, 2012). For further discussion on uncertainty see Section 1.1.2.

This scientific and technological development has partly led to an improvement in the spatial and temporal accuracy of weather forecasts (Hirschberg et al., 2011). However, such *"innovations in forecasting technologies are useless unless they are effectively communicated, understood, and acted upon"* (Demeritt et al., 2013, p. 174). Issues of (risk and crisis) communication and cognition are prominent topics of social science research and human geography (see Section 1.1.1). To ensure the usefulness of forecasting technologies for society, a strong need for integrating social science and atmospheric research has been proclaimed (e.g. Demuth et al., 2007; Hirschberg et al., 2011; NRC, 2006, 2010). Despite early efforts by social scientists to engage with atmospheric science like the Weather and Society * Integrated Studies (WAS*IS) program (Demuth et al., 2007) in the US, very little has been done in Europe (for exceptions see, e.g. Demeritt et al., 2016; Nobert et al., 2010; Rossa et al., 2011). On a global scale, the World Weather Research Programme (WWRP) of the World Meteorological Organisation (WMO) launched The Observing System Research and Predictability Experiment (THORPEX) focusing on the advancement of NWP (Parsons et al., 2017; Shapiro and Thorpe, 2004). Within THORPEX the Societal and Economic Applications (SERA) working group focused on the "*communication and decision processes that affect perceptions, behaviour, and outcomes*" (Parsons et al., 2017, p. 824).

Weather forecasts and warnings are issued by national weather services and private weather companies with the aim of preventing loss of life, injuries or damage (for more detail in the weather warning system in Germany see Section 1.1.3). They are still predominately issued as deterministic ('full certainty') forecasts, irrespective of the fact that verification reveals a high degree of uncertainty (Ebert et al., 2013). Uncertainty is an often misunderstood and therefore confusing expression for users of weather forecasts (NRC, 2006; Rossa et al., 2011; Spiegelhalter et al., 2011, p. 148). The portrayal of uncertainty in a forecast was long viewed as a weakness instead of scientifically sound and useful (NRC, 2006). The communication of forecast uncertainty – with the notable exception of probability–of–rain forecasts featured on most websites – is not common and thus not well known in Germany (Gigerenzer et al., 2005; Pardowitz et al., 2015).

Nevertheless, there are both theoretical and operational arguments for the benefits of communicating probabilistic information, which highlight for instance the gain in lead time to enhance preparedness and the adequate allocation of resources (e.g. Hirschberg et al., 2011; Ramos et al., 2013; Richardson, 2000; Roulston et al., 2006; Zhu et al., 2002), the increase of the plausibility of the forecast and the credibility of the forecaster (e.g. LeClerc and Joslyn, 2012), or emphasise the public's right to be informed (e.g. Johnson and Slovic, 1995).

To achieve such aims Morss et al. (2008b, pp. 336–337) identified five priority themes for weather-related SERA research selected due to their connection between societal needs and interests in weather prediction community: "*[. . .] understanding the use of forecast information in decision making; communicating weather forecast uncertainty; developing user-relevant verification methods; estimating the economic value of weather forecasts; and developing decision-support systems and tools.*"

This thesis will thus elaborate on the understanding, communication and use of uncertainty as the basis for further research on the application of forecast uncertainty in weather information and warnings in Germany.

In the next section the main research topics and how they are connected to geographical research are briefly introduced (Section 1.1). The following section provides an overview of the objective and the outline of this thesis and presents the overall research questions (Section 1.2). The Chapters 2, 3 and 4 represent the three individual papers. The thesis ends with concluding remarks in Chapter 5.

1.1 Scientific Background and Terminology

Extreme natural events are generally characterised as high-magnitude and low-frequency events, whereby the magnitude of an event refers to its energy, mass, or volume and –

with respect to weather events – is reflected in ascending terms like wind, storm, and hurricane. Frequency generally refers to the recurrence interval, the time-span between two events of a certain magnitude reflected in probabilities of occurrence or expressed in terms like 'hundred–year–event'. In spatial terms, we can in general differentiate between medium- and large-scale events like winter storms, and small-scale events like thunderstorms, differing in speed of development and occurrence and thus in warning (and response) lead time, event duration and sphere of action (Alexander, 1999; Dikau and Weichselgartner, 2005; Fortak, 1982; Schrott and Hufschmidt, 2017). Influenced by the event characteristics and features of exposure to a specific weather phenomena, such as the local topography, weather forecasts are one way to anticipate the future development of the atmosphere (Daipha, 2012; Fine, 2007) and give information about the intensity and the temporal-spatial characteristics of a weather event (see Fig. 1.1). Medium and large-scale events like winter storms have a spatial extent of several hundred kilometres and a speed of development and lead time of hours to days. Small-scale events like thunderstorms have a spatial extent of several kilometres and a speed of development and lead time of minutes to hours (Dikau and Weichselgartner, 2005; Fortak, 1982; Schrott and Hufschmidt, 2017).

1.1.1 Hazards, Risks and Uncertainty in Geographical Research

Even very high magnitude events do not necessarily have to have a strong impact on society as they might happen in uninhabited areas or encounter a resilient society (Müller-Mahn, 2007; Pohl, 2008; Weichselgartner, 2002). This perspective turns from a process-oriented hazard analysis with a focus on the relation of an event's magnitude and frequency to an application- and impact-oriented risk analysis that highlights societal aspects of risk perception, risk communication and decision-making under uncertainty (Pohl, 2008; Renn et al., 2007; Renn, 2008).

Risk and uncertainty are ambiguous terms with different scopes and meanings which are not always compatible with each other (for further discussion, see Banse, 1996; Bonß, 1995; Gerhold, 2009; Renn, 1998, 2008; Stirling, 2003; Taylor-Gooby and Zinn, 2006;

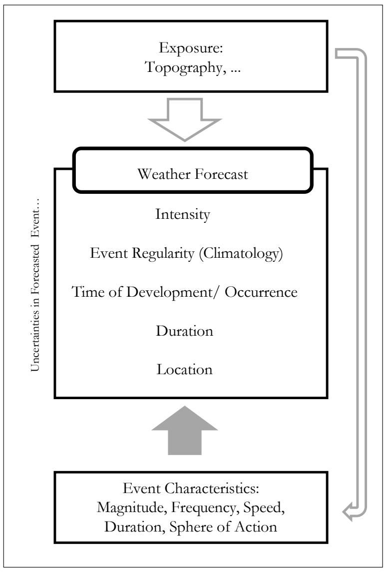

Figure 1.1: Event Characteristics and Weather Forecasts; compiled and designed by the author

Weichhart, 2007). From a non-fatalist, constructivist perspective, where hazards are not acts of god or an evil nature (Alexander, 1999), the concept of risk presumes a 'deliberate decision' to act (Luhmann, 1991), hence, it allows formability and thus the avoidance of negative impact by mitigation and prevention measures (Renn et al., 2007). Such a decision to (or not to) act is based on both (mathematical) probability estimations, and political and normative presumptions. Therefore, risk can be understood as both an analytic and a normative concept (Klinke and Renn, 2002; Renn, 1998; Renn et al., 2007) as the mitigation of impact is desired by most people and thus a societal mandate for governmental action. Any decision-making in disaster or pre-disaster situations is associated with uncertainty because such situations are usually characterized by their complexity and ambiguity regarding future developments (Klinke and Renn, 2002). Since these characteristics with respect to natural hazards incorporate both physical and human elements, geography "*is well situated to take a leading role in such investigations*" (Tobin and Montz, 2009, p. 521).

While the the focus of geographical hazard research remained on technical adjustment measures and risk assessments during the middle of the 20th century, social aspects gained greater priority by the 1960s and 1970s. First, psychological approaches challenged the claim of universal validity of the technical risk terminology.[2] Risk became a matter of subjective perception that could mean both a challenge or a benefit. By the mid 1980s constructivist approaches point to questions of communication, construction and prioritisation (Bonß, 2011; Felgentreff and Dombrowsky, 2008; Pohl, 2008).

Nevertheless, within geography – and in most affiliated scientific disciplines – hazard and risk research is (often clearly) split between physical science and social science (i.e. physical and human geography). Several classifications show the different approaches (e.g. Banse, 1996; Bechmann, 1997; Egner and Pott, 2010; Renn et al., 2007; Zinn and Taylor-Gooby, 2006). They share that each perspective can best be understood by their respective understanding of the concept of risk.

The physical and technical approaches aim to achieve a quantification of risks. Risks are regarded as objective facts of reality (i.e. of the nature), which can be calculated in principle, making them controllable with technology (Müller-Mahn, 2007; Pohl and Geipel, 2002). Risk is seen as a product of the event's magnitude or potential damage (e.g. number of potential deaths, damages or economic losses) and the probability of occurrence of an event at a specific place (Dikau and Weichselgartner, 2005).

Conversely, psychological approaches are interested in (subjective) perceptions, protective behaviour and individual assessments of risks and decision-making under (cognitive) uncertainty (Bechmann, 1997; Gigerenzer, 2013). Most prominent examples are the *prospect theory*, interested in the effect of potential value of gains and losses in risk-taking and risk-averse (to avoid risk) behaviour (e.g. Kahneman and Tversky, 1973, 1979) and the *psychometric paradigm*, interested in quantitative representations of risk attitudes and individual risk perception (e.g. Slovic, 1987, 2010).

Approaches from social science understand risk as unwanted events that have not yet happened, but are constructed as risks within society and science. Here, risks are always connected to (non-) knowledge or ignorance (Wehling, 2001). This issue will be further

[2] During that time, the works of Robert Geipel who studied social-geographic aspects in post-earthquake Friaul (Italy) in the end of the 1970s initiated geographical hazard research in Germany.

discussed in Section 1.1.2. There are several different perspectives on risk within social science, e.g. reflexive modernization (e.g. Beck, 2007; Bonß, 1995; Giddens, 1999), social systems theory (e.g. Luhmann, 1991), social anthropologist approaches (e.g. Boholm et al., 2013; Douglas and Wildavsky, 1983) or different postmodern approaches (for further discussion, see Fox, 1999).

Egner and Pott (2010) formulated a geographical risk perspective[3] that combines objectivistic and constructivistic approaches by using natural, social as well as cultural approaches. Contrary to the other disciplinary perspectives, geographical risk research tries to overcome the dichotomy between objectivism and constructivism by assuming the complementarity of both perspectives (ibid., pp. 18–19) and taking into account that both positions in their extreme interpretation cannot be logical justified.[4] In practice this is achieved by taking both risk concepts – and risk terminologies – into account.[5] In this sense, geographical hazard and risk research focuses on the (physical-geographical) identification of potential hazardous events, the estimation of the potential danger for values and life and the (subjective) perception and assessment of risk (Geipel, 1992; Müller-Mahn, 2007; Pohl and Geipel, 2002). This is represented in the perceptual and social science hazard research, the physical-geographical process-oriented hazard research and the application- and planing-oriented risk management (Pohl, 2008, p. 57). This thesis will follow the geographical risk perspective.

1.1.2 Further Reflections on Uncertainty

The subject of perception, communication of and dealing with uncertainty is highlighted as key factor in weather-related decision-making and has thus become a main topic in weather-related social science research (Daipha, 2012; NRC, 2006).

While most social scientists argue that uncertainty is always connected to a (known or

[3]For criticism of this concept and its proximity to social systems theory, see Pohl (2011) or Kuhlicke (2012).

[4]In the words of Renn et al. (2007, p. 132) radical constructivism easily gets into the vicious circle of putting everything into perspective while naive objectivism tends to deny cultural interpretation.

[5]This usually works fine as long as the risks refer to natural hazards regarding temporal-spatial issues.

unknown) lack of knowledge, most natural scientists tend to see uncertainty as generally probabilistic and assessable. Therefore, it has proven useful to distinguish between different kinds of uncertainty (see Fig. 1.2): uncertainty arising from the stochastic variability in known and observable phenomena is called aleatory uncertainty and uncertainty arising from a lack of knowledge, sampling errors or incomplete observations is called epistemic uncertainty (Brown, 2004, 2010; Cornell and Jackson, 2013; Faber et al., 1992; Merz and Thieken, 2005, 2009; Morgan and Henrion, 1990; Pate-Cornell, 1996).[6]

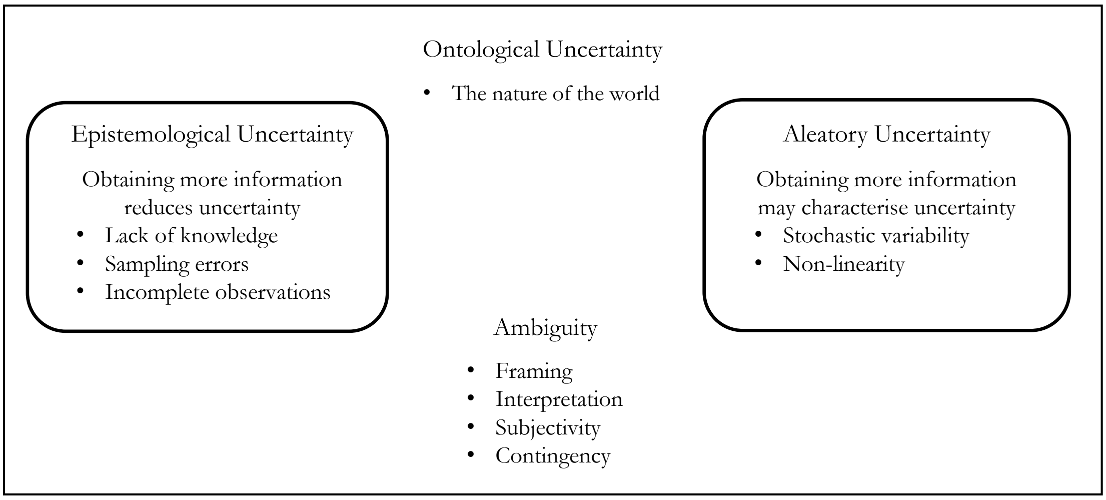

Figure 1.2: Uncertainties in Socio-Environmental Systems; compiled and designed by the author based on Brugnach et al. (2008) and Cornell and Jackson (2013, p. 519).

Generally, aleatory uncertainties in weather forecasts arise, e.g. from the chaotic character of the atmosphere, non-linearity and stochastic variability, while epistemic uncertainty arises, e.g. from incomplete knowledge about influencing factors and inaccuracy in weather observations and computer models (NRC, 2006; Steinhorst, 2009).

There are situations where this distinction has its limitations. For instance, when talking about socially constructed realities such as institutions and organisations, "*where*

[6] Other terms for aleatory uncertainty are, e.g. natural uncertainty variability, objective uncertainty, (basic or inherent) variability, (basic) randomness, or type-A uncertainty. Other terms for epistemic uncertainty are, e.g. subjective uncertainty, lack–of–knowledge or limited-knowledge uncertainty, ignorance, specification error, prediction error, and type-B uncertainty (Merz and Thieken, 2005, p. 115).

uncertainty is not framed with the concept of probability", it makes less sense to think about the inherent variability (Cornell and Jackson, 2013, p. 517). Therefore, some scholars distinguish further aleatory uncertainty from ontological uncertainty that "*relates to what the nature of the real world is, not the knowledge about the real world*" (ibid., p. 517). Thus, the understanding of ontological uncertainty depends strongly upon the understanding of and beliefs about the nature of reality, its entities and their interactions. Due to non-linearity and chaotic behaviour, ontological uncertainty resists the creation of statements or estimates about the future. The information about entities and their relations are simply not known as basis for such estimations (Brugnach et al., 2008; Cornell and Jackson, 2013; Curry and Webster, 2011).

Additionally, uncertainty about the uncertainty may arise as both the weather forecast and the forecasted weather event are "*subject to a range of interpretations concerning space and time, by lay users and by forecasters themselves*" (Handmer and Proudley, 2007, p. 85). Hence, a situation of ambiguity arises where framing assumptions influence the understanding, definition and interpretation of potential outcomes and options (Klinke and Renn, 2002; Renn et al., 2007; Stirling, 2003, 2010). Ambiguity can be understood as the "*epistemological link between the 'absence of certainty' and the subjectivity and contingency*" (Stirling, 2003, p. 42) or as "*something ranging from unanimous clarity to total confusion caused by too many people voicing different but still valid interpretations*" (Brugnach et al., 2008).[7] As there is no single legitimate interpretation of risk, this leads to the question of 'prioritisation' of options (Stirling, 2003, p. 45) and the assessment of risk situations and the implementation and use of potential mitigation measures (Renn et al., 2007, p. 166), which will be discussed in the following (see Chapter 4).

In social science, uncertainty is mostly discussed along its epistemological component (Bonß, 2011, p. 46) and thus the differentiation between uncertainty and knowledge has become most prominent. As discussed above, there are several different approaches within social science to risk and uncertainty in decision-making. Therefore, the mean-

[7] Interlingual differences may also occur. While the English language differentiates between safety, security and certainty, there is only one word in German: '*Sicherheit*' (Bonß, 2011, p. 44).

ing of the terminology strongly depends on what it is to be distinguished from. While earlier works subsumed uncertainty and probability under the term *error* in contrast to *irrelevance* (Smithson, 1989), epistemic uncertainty is now mostly understood as *uncertain knowledge* ('*Ungewissheit des Wissens*') in contrast to *ignorance* ('*Nichtwissen*') and (calculable) *risks* (Wehling, 2001, p. 472).[8] This distinction is important because epistemic uncertainty is generally seen as reducible, in contrast to the irreducible (ontological) character of ignorance. Faber et al. (1992) suggested a differentiation between *phenomenological* ignorance due to chaotic dynamics, and *epistemological* ignorance related to the structure of knowledge. The latter *"may be reduced by the accumulation and analysis of information"* (ibid., p. 227).

Weichhart (2007, pp. 206–207) distinguishes *uncertain knowledge* from *uncertainty* and *certainty* based on their attributed probability of occurrence. While certainty is characterized by a probability of either zero or one, uncertainty is characterized by a probability of anything between zero and one. Uncertain knowledge ('*Ungewissheit*') is characterized by contingency and is therefore not calculable. With its character of calculability the term uncertainty is close to the term risk in sense *"as a function of 'magnitudes' and 'likelihoods' of a determinate range of [negative] 'outcomes' "* (Stirling, 2003). Conversely, uncertain knowledge and ignorance are not identical with risk. On the contrary, they cover areas beyond known and observable risks and include potential surprises beyond the expectation based on risk assessments (Wehling, 2001, p. 466). In principle, uncertainty means non-knowledge of future events and simultaneously an acknowledgement of the possibility that a negative event may happen in the future (Bonß, 2011, p. 47).

Atmospheric processes and weather forecasts include all of the above mentioned forms of uncertainties. Geography is most interested in the measurement, modelling, visualisation[9] and the propagation of uncertainty. The questions how *"to convey knowledge*

[8] Please note that such differentiations have to be seen as ideal-typical textbook cases as there will be hardly any cases in which all action and decision-making processes that take place are known (Wehling, 2001, p. 472).

[9] The question about the visualisation of uncertainty or whether to communicate uncertainty in words

about uncertainty to the user" and what are *"the effects of uncertainty as information is processed"* (Goodchild, 2009, p. 1) are of specific interest in human geography.

1.1.3 The Weather Warning System of Deutscher Wetterdienst

Warning systems are a formalized way for anticipating future developments. In general, a warning system can be divided into three components: a *"detection or technical component (monitoring and detection, data assessment and analysis, prediction, and informing); an emergency management component (interpretation, decision to warn, method and content of warning, and monitoring of response); and a public response component (interpretation and response)"* (Mileti and Sorensen, 1990, p. 16). The detection component is largely the domain of scientific organisations for natural hazards, like a national hydro-meteorological service (NHMS), and depends on technology and science. The emergency management component is composed largely by emergency management officials of a local government. As emergency services like fire brigades themselves respond to warnings, they belong somewhere between the emergency management (the administrative part responsible for commanding and coordination) and the response component (the operational units).

Germany's NHMS Deutscher Wetterdienst (DWD) is the official source of information for warnings to ensure public safety. DWD's regional offices, each covering one or more of the 16 German states, are responsible for issuing weather forecasts and warnings to the general public and special user groups like road maintenance crews, the media, and civil protection for their respective region. The regional offices operate daily during daytime hours. In the night, the DWD main office in Offenbach is responsible for all weather warnings. There are special agreements for the dissemination of weather warnings and services (like instruction into user-specific warning tools) by DWD to fire brigades, the Federal Agency for Technical Relief (THW) and the German Red Cross (DRK). All other

or in numbers (Handmer and Proudley, 2007; Spiegelhalter et al., 2011) raises new questions about misunderstandings due to ambiguity and vagueness resulting from, e.g. the imprecision of terminology or more generally questions of literacy, numeracy or language difficulties (Morgan and Henrion, 1990; Pardowitz et al., 2015; Regan et al., 2002).

emergency services and voluntary aid organisations may receive assistance and advice.

All meteorological information follows the 'single-voice' principle, which should ensure consistent statements about weather related hazards among all governmental agencies (Weingärtner et al., 2009). Warnings regarding certain hydro-meteorological hazards (e.g. floods, avalanches) are provided by specialist units like flood forecasting centres operated by the German states as these warnings no longer concern primarily atmospheric processes, but subsequent ones. Since regional characteristics strongly shape the subsequent processes, the states are responsible for these warnings. DWD is not charged with the decision to declare a state of emergency due to severe weather events. Instead, this is the responsibility of the counties and major cities or in severe cases the states. DWD functions as official source of information and should give advice, but is not responsible for deploying any action based on this information such as evacuations. In case of emergencies, any communication to the public takes place through designated emergency management staff.

The official weather warnings in Germany are organised in a three-step process following an increasing sophistication of temporal and spatial resolution/precision: First, early warning information (*'Frühwarninformation'*) based on numerical models is incorporated by DWD into a 7-day risk assessment on medium term weather hazards (*'Wochenvorhersage Wettergefahren'*). This forecast includes information about expected severe large-scale weather phenomena and supra-regional (250–700 km) severe weather events with qualitative statements (possible, likely, very likely) about forecast uncertainty. Second, a weather watch (*'Vorwarninformation'*) is issued up to 48 to 12 hours before an expected regional (50–250 km) event. These forecasts are provided five times a day with different reports (*'Warnlageberichte'*) for the whole country and twelve regions respectively. The regions represent the larger German states or a combination of surrounding states. The focus is on all relevant weather phenomena and is designed to provide the user with an overview of the development of the situation (intensification, weakening) within the next 24 hours. It also includes observation data of present extreme events like gale-force storms. Within this period of 48 hours before a possible disruptive weather event, the development of the weather situation might be apparent but still uncertain. Besides the regional report a specific severe weather watch (*'Vorabinformation Unwetter'*) is issued, which should either be followed by a warning or be revoked. Third and ultimately, official (severe) weather warnings (*'(Un-) Wetterwarnungen'*) are issued on municipal level (on county level until 2016). Warnings follow a colour code corresponding to an intensification: yellow, ochre, red and purple. The lead times depend on the kind of weather event with a maximum of 12 hours. Severe weather warnings are issued for heavy continuous rain, hurricane gale-force wind, heavy snowfall, glaze frost, thaw periods, and thunderstorms (Weingärtner et al., 2009). During severe weather situations, updates on the development of the situation are compulsory. Yet, no probabilistic information is communicated in terms of numbers (Pardowitz et al., 2015).

A DWD forecaster issues a warning by drawing polygon lines around an identified area at risk. All affected municipalities and counties receive a weather warning. While weather warnings usually have a time stamp indicating the validity, severe weather watches and warnings need to be repealed via the same communication means as the warning message. A severe weather watch or warning ends when the forecaster no longer sees a threat in a particular weather event. This does not necessarily have to affect the validity of other warnings.

As there is always uncertainty about where exactly an event will occur, it remains uncertain whether an event will actually happen at a specific locality that received a warning. This might not be the biggest problem concerning large-scale events like winter storms, which have a larger sphere of action and impact. With small-scale events like thunderstorms, however, it can happen that an area receives a weather warning, but is ultimately not affected by the event. So, the warning recipient has the subjective perception of a false alarm from his location, although the warning is justified for the whole administrative area by objective criteria. In the domain of weather forecasting and warnings, a false alarm is a situation where a warning is issued but the event does not occur. On the other hand, a missed event describes a situations with a warning-event but no warning. The objective is to have a high detection rate and a low false alarm rate. Currently it is only possible to reach a higher detection rate by accepting a higher false alarm rate due to more warnings being issued (Weingärtner et al., 2009). A high false alarm rate might result in warning fatigue, dulling and desensitisation of the receiver regarding future warnings (Barnes et al., 2007; Dow and Cutter, 1998; Mileti and Sorensen, 1990; Ripberger et al., 2015).

1.2 Objectives and Thesis Outline

Several authors stress the gain in lead time to enhance preparedness and the adequate allocation of resources by communicating probabilistic information in weather forecasts based on NWP outputs (e.g. Hirschberg et al., 2011; Ramos et al., 2013; Richardson, 2000; Roulston et al., 2006; Zhu et al., 2002). It is assumed that providing this information allows forecast users to think about the upcoming situation and make decisions at an earlier stage of time under the constraints of given uncertainties.

This assumption underlies an understanding that the mitigation of impact is desired by most people. However, what people perceive as undesirable depends on their needs, requirements, values, preferences and the consequences of their (non-) actions (see, e.g. Frick and Hegg, 2011; Handmer and Proudley, 2007; Renn, 1998; Visschers et al., 2009).

In addition, different kinds of uncertainty exist within atmospheric processes, in weather forecasts and in the decision-making of forecasters, decision-makers in emergency services and the general public. How do users of weather forecasts perceive and interpret weather information and how do they make use of the information about uncertainty?

This thesis therefore addresses the following overarching research questions:

a) which factors influence the decision-making with respect to the perception of uncertainty in weather forecast; and
b) how do forecast users make use of probabilistic information and the additional lead time and how is the weather forecast (or warning) reflected in their decision-making?

The overall motivation for undertaking this research is based upon the research proposals for the research project *Wetterwarnungen: Von der Extremereignis-Information zu*

Kommunikation und Handlung (WEXICOM) phase 1 (2011–2014) and phase 2 (2015–2018) funded by the Federal Ministry of Transport and Digital Infrastructures (BMVI) within the Hans-Ertel-Centre for Weather Research (HErZ) conducted at Freie Universität Berlin (Simmer et al., 2016; Weissmann et al., 2014). The work is based on a mixed-methods design building upon three studies (see Tab. 1.1). The studies contain both qualitative and quantitative empirical social science methods, that is to say two questionnaire surveys and 27 semi-structured interviews. The studies address both the general public and the emergency management in Germany. The public and the emergency management were chosen as research subjects as they are stated in context of THORPEX as critical target user-groups for the use of weather forecast information (see Shapiro and Thorpe (2004, p. 45) and Morss et al. (2008b, p. 341)). Within emergency management, representatives from fire brigades and their control centres were especially selected as research subjects due to their importance in the context of operational implementation of weather warnings to maintain public order and ensure infrastructure safety (Geier, 2017). Fire brigades control centres are among the key addressees of weather warnings in Germany, but the importance of an adequate usage of warnings by the general public and other users – e.g. those in charge of transport, infrastructures and energy networks (e.g, Steiner et al., 2017) – must not be underestimated. For further descriptions of individual survey methods and sampling, see Sections 2.2.1, 3.2.3 and 4.2.

The investigation of the overarching research questions starts with an exploratory survey to prepare the research field (Chapter 2). The study contains a large number of open questions to identify new topics of interest, unknown problems, and research gaps in the field of communicating weather information in Germany. Emergency services were chosen as a target group as they have to deal regularly with weather hazards by profession and could thus initially be regarded as more sophisticated users of weather warnings.

The second study (Chapter 3) focus on the individual factors influencing the decision-making outlined in the first overarching research question. Here, the general public was chosen as research subject to have access to a broader and more diverse target group.

The third study (Chapter 4) again addresses the emergency management community. Based on the lessons learned from the two previous studies, this study dedicates itself in particular to the second overarching research question of how forecast users make sense of forecast uncertainty and lead time and how it is reflected in their decision-making.

Table 1.1: Overview of Studies Included in the Thesis

	Kox et al. (2015)	Kox and Thieken (2017)	Kox et al. (2018)
Target Group	Emergency Services	General Public	Emergency Services
Method	Questionnaire Survey	Questionnaire Survey	Semi-Structured Interviews
Sample Size	161	1342	27
Date	Sept – Oct 2012	Mar – Apr 2014	2012 – 2016
Research Question	A and B	A	A and B
Chapter	2	3	4

Table 1.1 provides an overview of the studies included in this thesis containing the respective overarching research question and the survey's target groups, methods, samples and dates. Each study has its own set of research questions, which break down the overarching questions.

Please note the changes to the original texts of, e.g. the chapter numbering, the reference list, the arrangement of tables and figures, and the use of abbreviations. The language was adjusted to British English if necessary.

2 Perception and Use of Uncertainty in Severe Weather Warnings by Emergency Services in Germany

published as: Thomas Kox et al. (2015). "Perception and use of uncertainty in severe weather warnings by emergency services in Germany". In: *Atmospheric Research* 158-159, pp. 292–301.

2.1 Introduction

Severe weather warnings are, as weather forecasts in general, uncertain (NRC, 2006). Uncertainties in weather warnings arise from the chaotic character of the atmosphere, incomplete knowledge and inaccuracy in weather observations and computer models (NRC, 2006; Steinhorst, 2009).

Although widely used, the term uncertainty is generally not well defined and meanings differ between scientific disciplines and authors. Especially in interdisciplinary research, as social scientists and natural scientists often have a different understanding of the calculability of uncertainty: while social scientists argue that uncertainty is always connected to an unknown lack of knowledge, natural scientists tend to see uncertainty as probabilistic and assessable (Banse, 1996; Weichhart, 2007).

Altogether, uncertainty is an often misunderstood and therefore confusing expression for forecast users, and communicating uncertain weather warnings is a difficult task even to experienced users such as emergency service personnel. A first step to define uncertainty is to distinguish between these perspectives by differentiating knowledge and randomness. With respect to the latter, uncertainty arises from the stochastic variability in known and observable phenomena (and is called aleatory uncertainty) (NRC, 2006; Pate-Cornell, 1996). In this way, uncertainty can be understood by the aspect of probability of occurrence and would thus be seen as generally quantifiable (Weichhart, 2007).

Secondly, uncertainty arises from the lack of knowledge or incomplete observations (and is called epistemic uncertainty). As the entirety cannot be completely known, it is generally not quantifiable (Pate-Cornell, 1996). Since some rare events happen unexpectedly, e.g. because there is no observed record of events, incalculable epistemic uncertainty is always part of aleatory uncertainty. This missing knowledge leads to uncertainty about the uncertainty or *"second-order uncertainty"* (NRC, 2006, p. 27) and is called ambiguity (Ellsberg, 1961) or vagueness (Colyvan, 2008).

EPS are one way to make estimates about the (aleatory) uncertainty of a weather forecast. However, while a weather forecast can be enhanced by quantifying this uncertainty, the ambiguity associated with the interpretation and communication of the forecast remains (Handmer and Proudley, 2007).

So far the topic of perception and use of uncertainty in weather information has mainly been addressed in the US and United Kingdom (UK), maybe due to a wider use of probabilistic information in weather forecasts in these countries (Gigerenzer et al., 2005). Some of the early studies (e.g. Murphy et al., 1980; Sink, 1995) came to the conclusion that more emphasis should be put into meteorological education to enhance people's knowledge about numerical weather prediction. Other studies (e.g. Gigerenzer et al., 2005) demand more emphasis on improving the communication of statistics. However, some more recent studies (e.g. Frick and Hegg, 2011; Morss et al., 2008a) concluded that understanding meteorological definitions correctly is not of preferential importance, as ultimately users have to infer the information to their subjective preferences and make their individual assessment of the situation.

The general perception of probabilities and uncertainties by the public has been addressed in several studies (e.g. Kahneman and Tversky, 1979). Most studies in the context of communication of weather forecasts and warnings are conducted with laypersons (e.g. ABM, 2009; CFI, 2005; Joslyn and Savelli, 2010; Morss et al., 2008a; Sink, 1995) or based on psychological experiments amongst university students (e.g. Joslyn et al., 2009). Little is known, however, about how emergency service personnel perceive this information and make use of it (Frick and Hegg, 2011; Handmer and Proudley, 2007; Steinhorst, 2009). The question how to communicate weather warnings, especially to emergency services, has to be addressed separately from the communication to the general public, because this user group differs from other groups and the general public regarding its needs and requirements (Demeritt et al., 2007; Visschers et al., 2009). Only a few studies address emergency management experts (e.g. Demeritt, 2012; Frick and Hegg, 2011; Punkka and Rauhala, 2011) or show a sampling mixture of both laypersons and experts (e.g. Handmer and Proudley, 2007). While surveys with laypersons usually have big samples consisting of several hundred (e.g. Sink, 1995) or thousand (e.g. CFI, 2005) participants, expert surveys usually have smaller samples consisting of several dozen (e.g. Frick and Hegg, 2011) or a few hundred (e.g. Demeritt, 2012; Punkka and Rauhala, 2011) persons.

Based on these studies, research gaps include the topics of understanding, interpretation and use of weather warnings (e.g. Morss et al., 2008a). Visschers et al. (2009) point out that only little research has focused on user specific tailored information, while Morss et al. (2008a) criticise that most study designs have experimental character and miss out real-world settings. Whereas almost all studies come from the US, with some exception of Switzerland, Scandinavia and the UK, no scientific study addressing emergency services has been conducted in Germany so far.

This paper starts with a methodological overview, presenting the survey procedure and the questionnaire design. Then survey results regarding the communication of weather forecasts and warnings will be discussed. A special focus is on the perception of uncertainty and the use of probabilistic information by emergency services in Germany.

2.2 Methods

An explorative approach was chosen to gain new knowledge about perception and use of uncertainty amongst the emergency management community in Germany. Thus, an online survey was conducted between September and October 2012. An online approach was chosen to enable the participation of a broad range of experts within Germany in short time. In this study experts are defined as professional users of weather information in emergency services, civil protection or affiliated fields. In preparation of the survey qualitative expert interviews took place mainly with representatives from DWD and Fire Brigades in order to identify the key questions and to identify potential experts.

2.2.1 Sample and Survey Procedure

Since most experts could be identified within administrative agencies, a snowball sampling technique was used to recruit participants starting with existing administrative contacts of DWD: Users of the Feuerwehr-Wetterinformationssystem (FeWIS) tool – a DWD weather warning tool especially designed for emergency services – and other professional warning users of DWD were provided with a link to the online questionnaire via email and were asked to forward it to their colleagues. The survey took place between September 17th and October 12th 2012 and all contributions were kept anonymous.

In total 161 experts completed the questionnaire. 89 participants were fire fighters, with 40 of them being professional fire fighters, 13 voluntary fire fighters, 5 plant fire fighters and 30 working in an emergency service command centre.

6 participants represented various federal agencies, 9 participants represented a state agency (Environmental Ministries and Interior Ministries), and 34 participants represented a communal or regional agency (District Government, City Council or likewise). The remaining 23 were either policemen, paramedics, or other emergency managers from, e.g. transport or relief organisations. The high number of participants from fire departments and communal administrative well reflect the German emergency management system which is mainly organised on that level.

2.2.2 Questionnaire Design

Based on a preliminary work, a semi-standardised questionnaire was designed (see Appendix A). It consists of 20 questions, eleven closed-ended and nine open-ended questions. The open-ended questions had to be answered by typing in free format text, either just key statements or longer remarks. The questionnaire contained questions about communication tools and content of weather warnings, problems with communicating and receiving weather warnings, dealing with uncertainty in weather forecasts, confidence in weather warnings, decision thresholds, lead times and finally the experts' affiliation. Note that not all of the questions will be discussed here.

The results of the closed-ended (quantitative) data were evaluated using mainly descriptive statistics, whereas the open-ended (qualitative) answers were analysed with a structuring content analysis (Mayring, 2001). While some of the closed-ended questions were adaptations from other studies (ABM, 2009; CFI, 2005; Demeritt, 2012; Joslyn and Savelli, 2010; Morss et al., 2008a; Patt and Schrag, 2003; Sink, 1995), most of the open-ended questions resulted from key topics identified during the preliminary expert interviews. This approach was chosen to enable comparability of results on the one hand, and to address new topics and gain further expert information on the other hand in order to emphasise the explorative character of the survey.

2.3 Results and Discussion

The questionnaire started with simple multiple choice questions regarding communication tools and content to build up participants' confidence with the survey. Open-ended questions then alternate with the closed-ended ones.

The first question addressed the weather phenomena, which are relevant for the participants' work as emergency service personnel (Tab. 2.1). It is not surprising that strong wind and heavy rainfall were ranked as relevant for most of the users, as winter storms are one of the major natural hazards in Europe (Donat et al., 2011). Those events tend to cause most harm to people and property (GDV, 2012) and therefore are of major

Table 2.1: Most Relevant Weather Phenomena for Emergency Services (n = 161; row percentage, multiple answers allowed)

Weather phenomena	%
Strong wind and gusts	92
Heavy rainfall	85
Thunderstorms	58
Snow	46
Glazed frost	44
Hail	44
Continuous rain	37
Thawing	18

interest to emergency services. A further more general open-ended question (Question 2) enquired about the mitigation measures which are regularly taken into account when dealing with severe weather. According to the participants' answers four major topics (no rank-ordering) of mitigation measures could be identified by clustering all given answers using structuring content analysis: First, the survey participants state that *intensified observation* (including the consultation of the weather service's regional office via telephone for more detailed information) is one of the main measures, which follow up a severe weather warning. Secondly, some of the participants state that they just *forward information* (including, e.g. internal staff, municipalities and outdoor event organisers) after receiving a warning. This might be due to the gateway role of, e.g. command centres and the fact that most warning recipients are not necessarily the ones to undertake ad hoc measures on the ground. The latter becomes clearer when looking at the two remaining mitigation measures, which are also of a more strategic nature. First, *personnel preparatory measures* are stated. This includes the call-up of off-duty units or extending the length of service. In addition, *non-personnel preparatory measures* are also taken into account. Inter alia, they include situation assessments and the deployment or relocating of technical equipment.

It has to be mentioned that the question was not related to a specific event and did not include when mitigation measures were taken or who within the organisation was involved. Such more detailed questions about mitigation measures will be addressed in a follow-up study.

2.3.1 Communication of Weather Forecasts and Warnings

Experts stated that the DWD is not the exclusive source communicating weather information to emergency services. About 37 % of the participants state that they or their organisations serve as a gateway to communicate weather warnings to related organisations, either in a top-down communication chain within the organisation or towards affiliated local agencies. In addition, they forward information to selected local businesses or to organisers of public outdoor events (Question 3). DWD is the only agency to issue official warnings by law (single-voice-principle). In addition, some private weather companies provide standard weather information to the general public. Nevertheless, problems which might occur due to that, will not be addressed in this paper, but should be considered for further investigations. The official weather warning system in Germany is organised in a three-step process. Early warning information (*Frühwarninformation*) is based on numerical models including EPS forecasts. They are implemented by DWD into a 7-day forecast (*Wochenvorhersage Wettergefahren*) for public use. This forecast includes information about expected severe large-scale weather phenomena and severe weather events with qualitative statements about forecast uncertainty (discussed later).

Secondly, an alert or watch (Vorwarninformation) is issued up to 48 to 12 h before an expected event. These forecasts are provided five times a day with different reports (*Warnlagebericht*) for the whole country and twelve regions respectively. The regions represent the larger German states or a combination of smaller ones. Ultimately, warnings are issued on county level. The lead times depend on the kind of weather event with a maximum of 12 h (Weingärtner et al., 2009).

Some questions in the survey dealt with communication problems the participants might have experienced while receiving or forwarding weather warnings within the emergency community. Open-ended questions (Question 4 and 5) provided detailed information about such communication problems and results will only be presented briefly at this point. The participants indentified the following major problems (no rank-ordering): a) short warning lead times, which do not correspond with the users' needs, b) too many warnings, which may result in a dulling or crying wolf effect, c) misinterpretation of weather information, d) dealing with uncertainty in weather forecasts and warnings, e) inappropriateness of warnings with respect to geographical characteristics of the warning area (i.e. size, topography, etc.), f) conflicts between official warnings and information provided by others or own observations, and g) some technical problems receiving the warning. Some of these problems are discussed below, with the main focus on the uncertainty issue.

2.3.2 Perception of Uncertainty in Weather Forecasts and Warnings

Confidence in weather forecasts and warnings

Confidence in weather forecasts is not directly related to the understanding of forecast uncertainty (Morss et al., 2008a). But it can give a hint about the participants' perception of weather forecast and their expressions of second-order uncertainty (NRC, 2006).

In risk perception and communication research the distinction between confidence and trust has proven to be useful (Frick and Hegg, 2011; Luhmann, 2000; Siegrist and Cvetkovich, 2000; Siegrist, 2001). While trust refers to the reliability of information source and the informant (Frick and Hegg, 2011), confidence refers to experience and evidence (Siegrist, 2001). Thus, the question about trust aims at the experts' trust in the Meteorological Service or the media in general, whereas the question about confidence refers to someone's own association towards the reliability of a weather forecast or a warning.

It can generally be assumed that there is a negative correlation between the level of knowledge about a specific hazard and people's trust into involved stakeholders (Luhmann, 2000). In other words, the less knowledge someone has about a hazard, the more he trusts people in charge and their estimations (Siegrist and Cvetkovich, 2000). In reverse that means, that the more knowledge someone has about a specific issue, the less he relies on the assistance of others. Thus, trust is important in situations where the essential knowledge for decision making is missing (Siegrist, 2001).

It can be assumed that the meteorological knowledge of the emergency service personnel involved in this survey can be ranked slightly higher than the meteorological knowledge of the general public, due to their daily exposure to weather warnings and hazards, regardless of differences within the group of experts.

In the survey the topic of confidence was addressed with the question "How high is your confidence in the accuracy of a 2-day/7-day forecast regarding a) temperature, b) chance of precipitation, c) amount of precipitation, d) chance of thunderstorm or e) chance of storm?" (Question 6).

A matrix was provided so that the different forecasts could be answered separately. Scaling was pre-defined by the terms very low, low, high and very high (Fig. 2.1). Tem-

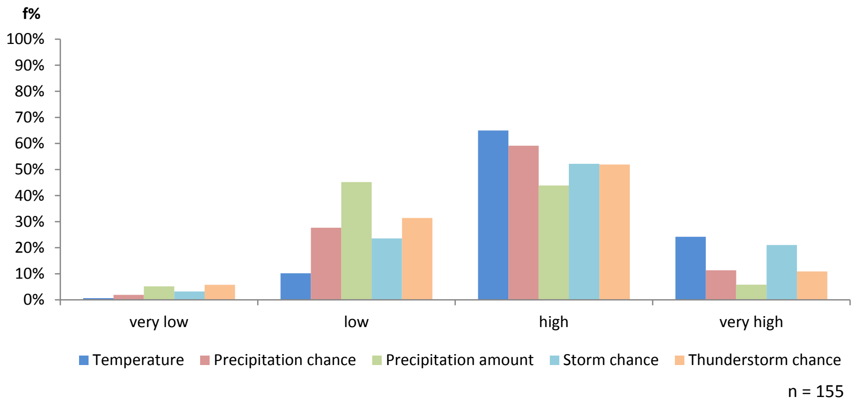

Figure 2.1: Confidence in 2-Days Forecasts; compiled and designed by author

perature forecasts achieve the highest ranks in confidence and forecasts concerning the amount of precipitation the lowest. 89 % of the participants rated the confidence in a 2-day temperature forecast as high or very high. The chance of storm and chance of precipitation forecasts were rated by the participants as high or very high with 73 % and 70 % respectively. The values decrease to 63 % for chance of thunderstorm forecasts and only 50 % to forecasts of amount of precipitation. It becomes apparent that confidence in forecasts addressing absolute values, like amount of precipitation, is lower than the con-

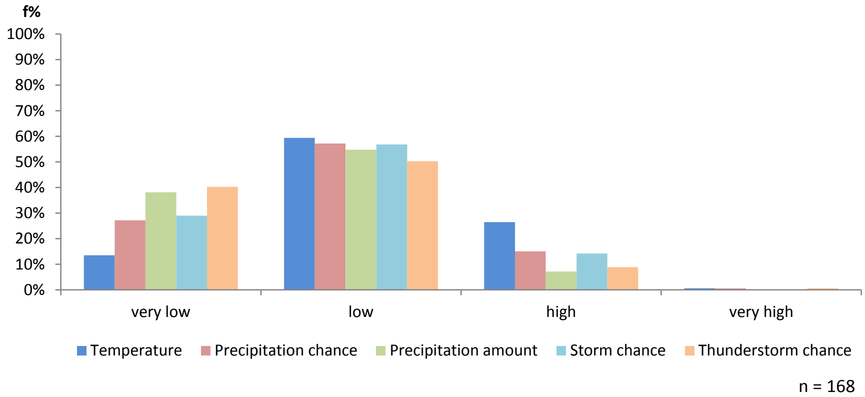

Figure 2.2: Confidence in 7-Days Forecasts; compiled and designed by author

fidence in forecasts addressing probabilities. These results correspond with other studies referring to laypersons (Morss et al., 2008a).

It also becomes clear that the participants have a good conception about the skill of weather forecasts, as 2-day temperature forecasts are generally more accurate than probability of precipitation forecasts or even forecasting the correct amount of precipitation (Balzer, 1994). Likewise, the local chance of thunderstorm occurrence is hard to estimate and therefore correctly indicated with lower confidence by the members of the emergency services.

Compared to the 2-day forecast, the confidence in 7-day forecast is lower, with the ratio of the respective weather phenomena remaining equal (Fig. 2.2). Again, the fact that forecast uncertainty generally increases with forecast lead time (NRC, 2006) is correctly indicated by the participants of the survey (Joslyn and Savelli, 2010; Morss et al., 2008a). Various reasons for these responses can be considered: As pointed out, confidence is highly depending on individual experiences. The experts gain knowledge not only in their daily work routine when dealing with weather warnings, but also in their everyday life. Temperature forecasts and probability of precipitation are common formats in media communication in Germany (Gigerenzer et al., 2005) and thus experts' experience with these formats can be considered as rather high. Furthermore, it could also be argued that the survey participants *"remember some forecast errors better than others and this in turn effects the estimated frequency"* (Joslyn and Savelli, 2010, p. 190). Hence, the participants are more conscious of uncertainties in some forecasts then in others. Also, the correct phrasing of a forecast – meaning the verbalisation or the presented format – can have an effect on users' information assessment. Sink (1995) shows that wrong or ambiguous use of terms can lead to misunderstandings and eventually result in unintended reactions.

Uncertainty in weather forecasts and warnings

Already in 1980 Murphy et al. recommended that probability information should be included into weather forecasts in order to communicate forecast uncertainty. They came to the conclusion that people, misunderstanding probabilistic predictions, also misunderstood 'traditional' or deterministic weather forecasts. Hence, not the statement about probability, but rather the predicted weather phenomenon was misunderstood. They conclude that intensifying public's meteorological education was necessary. Gigerenzer et al. (2005) argue that people's confusion with probabilities is related to a missing reference: *"to improve risk communication with the public,experts need to specify the reference class, that is, the class of events to which a single-event probability refers"* (p. 623). They conclude that the public has to be better educated in statistics. However, Morss et al. (2008a) point out that the correct meteorological definition is not always needed for decision making, yet the likelihood of an event is sufficient on its own. They argue that *"even if people knew the technical correct interpretation, they would still have to infer what it meant for their interests"* (ibid., p. 983).

It is not only a limited meteorological or statistical knowledge that leads to misunderstandings of (probabilistic) weather forecasts. Furthermore, the chosen format by which a forecast is communicated is an additional source of ambiguity. The forecast itself and the perception of the used formats are sources of greater uncertainty or ambiguity than the predicted event or the interpretation of the weather phenomena (Handmer and Proudley, 2007). The question is, if information should be best communicated, e.g. via text, absolute or relative value, via diagrams or graphics (Ibrekk and Morgan, 1987; Morss et al., 2008a; Patt and Schrag, 2003; Visschers et al., 2009). In a broader sense the question is also, if information has to be provided as a deterministic statement, that is for instance information about amount or speed, or if forecast uncertainty can be useful to the users and should therefore as well be provided. In turn, this is followed up by the question which uncertainty format fits best to address users' needs. As stated above, uncertainty can be presented by using relative frequency or probability (e.g. Joslyn et al., 2009), various graphic visualisations (e.g. Monmonier, 2006; Spiegelhalter et al., 2011) or verbal statements (e.g. Patt and Schrag, 2003). Even though many studies address this topic, there is still some research needed on the format to present and communicate uncertainty in weather forecasts (Joslyn et al., 2009; Morss et al., 2008a).

In this survey the topic of uncertainty communication was first addressed by a question relating to users' favoured format for medium range weather forecasts, meaning a 7-day forecast. The single-choice question had three pre-defined answers: single values, range of values, or probabilistic values. In the questionnaire each possible answer was additionally illustrated by a descriptive forecast statement (Question 7).

There are two possible ways to understand uncertainty in this case. First, range of values and probabilistic values can both be seen as a statement about uncertainty. E.g. Morss et al. (2008a) rate all communication formats other than a single valued prediction as a statement about uncertainty. In reverse, the use of single valued prediction would be seen as a deterministic statement.

Secondly, single values and range of values can both be seen as statements related to thresholds. Both deal with concrete numbers and values which could be applied to those threshold emergency services used within their organisations. Indeed, probabilistic values could as well be related to thresholds, for instance, if decisions are linked to different degrees of likelihood of an event, but this does not correspond to the common practice in Germany.

The analysis shows that a compulsory declaration of single values seems not necessary. Only 6 out of 161 participants preferred using deterministic forecasts rather than probabilistic range forecasts. On the contrary, the use of a range of values and probabilities reaches higher consent (107 and 48, respectively).[10] It is possible that the participants

[10]In relative terms (4 %, 66 %, 30 %) these results fit with findings from other studies, e.g. 10 %, 59 %,

grasp meteorology not as an exact science as it does not provide them with clear and robust single-valued predictions, or that the participants know from experience that commonly no single-valued predictions are made for a middle range forecast. In addition, it might as well be that the participants chose the category range of values out of their practical knowledge, if they use thresholds in their daily work with weather forecasts and therefore have a need for 'set numbers', although neglecting the need for the declaration of single values. But the participants' favour for probabilistic range forecasts does not necessarily mean that users can ultimately resign deterministic statements for their daily work. Thus, it was asked to what extent the users rely on deterministic forecasts, such as detailed information about expected amount of precipitation or wind speed (Question 8). 85 % of the participants confirmed the need of such deterministic statements. Only 15 % stated that they could work with probabilistic information. This relation does not vary much with participants' affiliations.

The question whether uncertainty should be better communicated via verbal or numerical terms was asked separately, because of the assumption that these formats are a major source of uncertainty and ambiguity (Visschers et al., 2009). This is particularly the case with verbal statements about uncertainty (Rogell, 1972). The problem is that verbal statements themselves are highly ambiguous or vague and consequently a source of further uncertainty. Colyvan (2008) points out that one can differentiate between four different kinds of uncertainty of linguistic origin. He distinguishes context dependence, underspecificity, ambiguity and vagueness. While *context dependence* points to the fact that a statement fails to specify the context in which the term is to be understood, *underspecificity* points to the fact that the term is not as specific as needed. Uncertainty arising from *ambiguity* means that a word can be used in more than one way and it is not clear in which way it is being used from the given context. Finally, *vagueness* is a source of uncertainty arising from unspecific use of a term in a borderline-case sense.

DWD is currently not using numerical expressions of uncertainty in its general weather

31 % in a 2005 study for National Oceanic and Atmospheric Administration (NOAA) regarding laypersons (CFI, 2005).

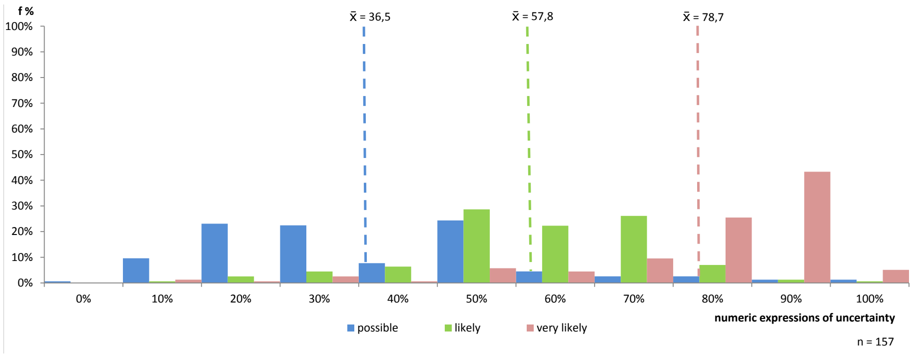

Figure 2.3: Numeric Associations to Verbal Expressions of Uncertainty; mean values: 36.5% (possible), 57.8% (likely), 78.7% (very likely); compiled and designed by author

warnings. As briefly addressed above, the 7-day forecast on weather hazards (*Wochenvorhersage Wettergefahren*) uses only verbal state- ments about uncertainty. The terms possible (*möglich*), likely (*wahrscheinlich*), and very likely (*sehr wahrscheinlich*) are used by default. None of these terms are related to an explicit numerical value.

In the survey participants were asked to assign numerical values to these verbal statements (Question 9). The values 0 % to 100 % were pre-defined in 10 % steps for each of the verbal statements. Results[11] show that nominations scatter extremely (Fig. 2.3) and cover almost the whole range of probabilistic associations for all three verbal statements from 10 % (even 0 %) until 100 %. In addition, an overlapping of verbal statements can clearly be seen.

This extreme dispersion is a good example of uncertainty within the verbal statements themselves. Especially the term possible is highly underspecific and thus subject to major variability in interpretation. In addition, the linguistic proximity or vagueness (shown by the overlapping) of statements DWD uses in its weekly forecast, is a further source of errors. Hence, all terms together are highly ambiguous as it is not clear in which way they should be used correctly. Adding now numerical probabilities and thus aleatory uncertainty results in a 'doubled' uncertainty (Sink, 1995) whatever source the linguistic uncertainty arises from.

[11]Comparing the mean values Sink (1995) and Rogell (1972) came to similar associations with their studies regarding laypersons.

To what extent this effects the interpretation and use of weather warnings is a need for further research. But it seems almost certain that for the use of probabilistic information in weather forecast and warnings such aspects should not be disregarded.

2.3.3 Use of Uncertainty in Weather Forecasts and Warnings

After receiving a warning, users have to be able to take action and make use of the forecast by converting the warning into a mitigation measure. Here, the lead time between receiving a warning and starting first mitigation measures matters. It is commonly indicated in minutes, hours or days. This time spread can massively vary depending on the organisation and the measure undertaken (Joslyn and Savelli, 2010). In addition, a forecast might also be seen as a turning point from which reactions towards a predicted event are implemented (Demeritt, 2012; Joslyn and Savelli, 2010). In this study several questions covered the topic of how a forecast is applied by end-users.

One question asked which lead time the organisation needed to start with first preparatory measures (Question 10). Participants were asked to answer this open-ended question providing time data. 155 of the 161 participants answered this question. Afterwards statements were classified for better analysis. Classification was made according to organisational aspects, such as work day or shift work, and the meteorological predictability: For short range forecasts the latter is commonly subdivided into short range forecasts (72 h), shortest range forecasts (12 h) and nowcasting (up to 2 h). These three forecast types vary in the use of forecasting tools and especially in forecast skill regarding different weather phenomena.

Results show that again nominations scatter considerably (Fig. 2.4). Main differences become clear comparing the statistical values. The range of nominations starts with 10 min and ends with up to 7 days. Especially the outlier is extreme. Nevertheless, approximately 50 % (median value) of the organisations need a lead time of less than 3 h for a general mitigation measure. Even if it is obvious that the chance for or intensity of implementation of a preparatory mitigation measure varies with lead time, the maximal values are surprisingly high. On the one hand, this might be related to the fact that the

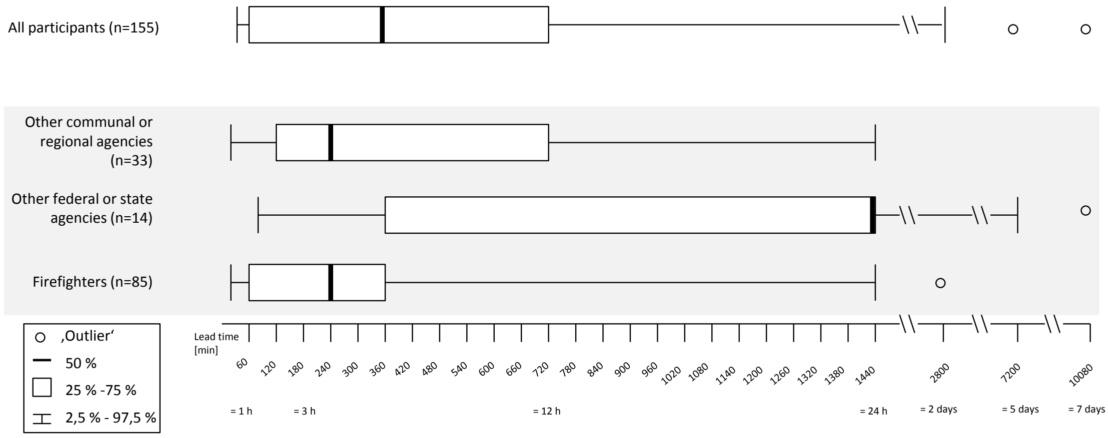

Figure 2.4: Organisational Lead Times Needed for Preparatory Actions (Boxplots, all participants and selected subgroups); compiled and designed by author

experts see preparatory measures as extensive and well prepared measures instead of ad hoc solutions. Therefore, they state the upper end of the time spread. It can, however, not be concluded from these statements, whether they or their organisations can deal quicker with the hazard if necessary. Secondly, it might also be possible that the participants did not know the meteorological constraints of weather warnings, thus overestimating forecasting abilities and thus came up with such long lead times. Yet it is striking that these results do not correspond with the operational practice of meteorological services and the possible lead times for thunderstorm or some winter storm forecasts (Weingärtner et al., 2009).

A second question was devoted to the understanding of lead time as a threshold or turning point (Question 11). Participants were asked to state the start of preparatory mitigation measures[12] due to information about the probability of occurrence. This question builds up on the assumption that uncertainty information at an early point

[12] As shown before, several different mitigation measures are taken into account. Addressing the lead times for different mitigation measures separately was shortly considered but then withdrawn due to the explorative character of the survey and the heterogeneous structure of the participants and their affiliations. The number of each case would have been too low to draw a conclusion. Although a threshold for a single measure does not necessarily have to correlate with all measures within an organisation, further research might consider addressing mitigation measures separately.

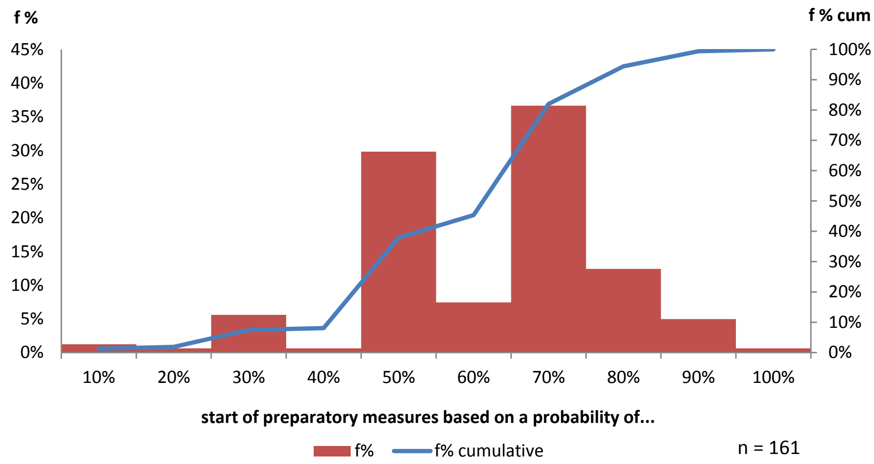

Figure 2.5: Preparatory Measures based on a Probability Threshold; compiled and designed by author

of a possible event can enhance the preparation of mitigation measures (Murphy, 1994; Palmer, 2002; Richardson, 2000; Roulston et al., 2006; Zhu et al., 2002).[13] Results show that 6 % of the participants would start with preparatory mitigation measures based on a warning with at least 90 % probability of occurrence. Still 55 % would only start above 70 % probability of occurrence. But 92 % of the participants would start above a 50 % chance of an event to occur. No single threshold category reaches an agreement of more than 37 % (Fig. 2.5). Again, that the distribution of nominations is extremely scattered is depending on individual risk perceptions (Joslyn and Savelli, 2010) but also on organisational factors. In his study for the British MetOffice Demeritt (2012) came to similar results and found that users do not want to react to forecasts of low probabilities.[14] Searching for explanations to these findings, Sink (1995) stated that also the phrasing of the question matters, because *"plans could mean something different to every person"* (p. 10). So, such answers should be examined carefully as further ambiguity is involved. There are almost uncountable sources of second-order

[13]e.g. Roulston et al. (2006) showed the economic value of such forecast information for road maintenance services.

[14]He concluded that this preferences are not in line with the *"scientific orthodoxy and [with] the government's emphasis on taking early and proactive action in response to emerging threats"* (Demeritt, 2012).

uncertainty of different influence on the perception by warning recipients. In the field of weather forecasting and warnings, extreme events may also be an influential factor on uncertainty perception and decision making. Joslyn and Savelli (2010) point out that *"the same probability (e.g. '30 %') applied to a more serious side effect (cancer) is considered greater than when applied to a less serious side effect (headache)"* (p. 190). In other words, the severity of consequences is assessed, and the effects of underestimating the more serious consequences are obviously higher than making less serious errors, especially if a person believes that he might be affected (Jungermann and Slovic, 1993).

But in this case the forecast user does not refer probability to likelihood (and thus to uncertainty) but to a specific risk. Contrary to some private enterprises (e.g. road maintenance services or energy sector), consequences of false alarms and missed events are difficult to quantify in the public sector and especially in case of emergency services. Costs and benefits of emergency services often do not apply to the same person or organisation, and governmental social responsibility and various non-monetary costs play a major role.

2.4 Conclusion

The perception and use of weather warnings have been addressed in several studies in the past, mainly in the US and UK. However, research on this topic has not been sufficient yet for Germany, especially for the emergency service community.

Uncertainty is an integral part of weather forecasts and thus a major issue with respect to communicating those forecasts and warnings. It must be distinguished between different sources of uncertainty. First of all, uncertainty arises from the stochastic variability in known and observable phenomena (aleatory uncertainty), and missing knowledge and incomplete observations (epistemic uncertainty). Furthermore, the lack of knowledge results in uncertainty about uncertainty (or second-order uncertainty). As shown, this is especially the case for verbal statements in weather warnings, which are often underspecific and ambiguous.

Statements about confidence in weather forecasts show that the emergency service personnel who participated in this survey generally have a good sense of second-order uncertainty in weather forecasts. However, this should not be regarded as a clear sign for preferring probabilistic forecasts, as the level of confidence in forecasts can only be an indication about the perception of second-order uncertainty.

Nevertheless, when trying to enhance weather forecasts by reducing uncertainty, one should not only focus on im- proving computer models and observation tools, but should not forget to keep an eye on the communication aspect of a forecast as well. Here, improvements might also be possible as inherent second-order uncertainty might be reducible. Colyvan (2008) points out that it might be the most obvious way to be more careful with the language. Thus, the wording of forecasts and warnings should be done accurately. Standardising the usage of numerical and verbal statements of probability could enhance weather communication. But regarding the overlapping and variability in interpretations (Fig. 2.3), uncertainty should better be communicated with range of estimates rather than giving a single-valued estimation. Nonetheless, words are still useful to describe uncertainty, because it avoids the problem that the forecasters have to reach consensus on a single probability estimate or otherwise completely omit uncertainty information (Patt and Schrag, 2003). In addition, some research (e.g. Wallsten et al., 1986) show that many people understand words better than numbers.

But while numeric expressions of uncertainty are objectively more precise than verbal expressions (Spiegelhalter et al., 2011), words are still used by people (forecasters and users) when they have to report and explain a probability to others (Visschers et al., 2009). The authors suggest to use a combination of verbal and numeric expression to ensure that on one hand people have the right information and on the other hand the forecast fits with users' preferences, needs and their level of understanding (Sink, 1995; Visschers et al., 2009). The survey results show that this varies amongst users. Thus, in order for them to be able to take effective action, tailored warnings could be appropriate. This idea was already brought up as an argument by Rogell in 1972, but as Visschers et al. (2009) point out, there is still research needed in this field.

Forecast end-users are a heterogeneous group (Doswell, 2003; Murphy, 1993). The survey results show that even within one specific group like emergency services the perceptions, needs and capabilities vary considerably. No single probability threshold could be identified for organisations to start with preparatory mitigation measures. But it became clear that emergency services tend to avoid forecast based on low probabilities as a basis for their decisions. This might be due to experts referring the probability statement not to the likelihood of an event but to possible consequences and thus to a specific risk. In the case of the emergency community those consequences are difficult to quantify. Furthermore, these thresholds are quite different from the numeric associations of verbal expressions of uncertainty. But while the latter shows the relation between wording and numeric probability based on a hypothetical forecast situation, the thresholds for starting preparatory mitigation measures refer to a (hypothetical) forecast situation addressing individual and organisational decision making and activeness. Beside the weather context, several other factors bias this decision making process: Such as the emergency service personal's individual expertise and scope of action, and the overall organisational culture, such as guidelines, financial and personal resources, or accountabilities (Fahlbruch et al., 2012).

More detailed research is needed in this field. Special attention should lie on addressing the consequences of weather and weather warnings. Due to the limited potential for quantitative methods, qualitative methods should be applied in further research. Interviews and in-field observations could be appropriate tools to gain more information about this specific topic.

3 To Act or Not to Act? Factors Influencing the General Public's Decision About Whether to Take Protective Action Against Severe Weather

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3.1 Introduction

Weather forecasts and warnings in Germany are, with the notable exception of probability–of–rain forecasts featured on most websites, communicated deterministically to the public and professional end-users, although research suggests that providing end-users with additional information about the forecast uncertainty of a possible event can enhance the preparation of mitigation measures (Hirschberg et al., 2011; LeClerc and Joslyn, 2012; Murphy, 1994; NRC, 2006; Palmer, 2002; Ramos et al., 2013; Richardson, 2000; Roulston et al., 2006; Zhu et al., 2002).

Uncertainty information can be communicated in terms of probabilities, frequencies or confidence intervals, in the form of numbers, as verbal descriptions or as graphical representations (Skubisz et al., 2009).

Often decisions concerning the preparation of mitigation measures must be made early, when the probability of severe weather events is low (Joslyn and LeClerc, 2012). However, in a study with members of emergency services in Germany, Kox et al. (2015) showed that less than 10 % of the participants would start to take action based on a forecast probability of 40 % or lower for a violent storm to take place on the next day. No single threshold category could reach a majority consensus. The authors assumed that *"beside the weather context, several other factors bias this decision making process: [...] individual expertise and scope of action, and the overall organisational culture"* (Kox et al., 2015, p. 300).

But what does a lower or higher probability threshold for taking action mean? First of all, weather forecasts per se do not possess an intrinsic value in an economic sense (Murphy, 1993, 1994). They only have a specific value if a user takes action and this action saves him/her money as a result because the action avoids (higher) damage costs (Murphy, 1993, 1994; Mylne, 2002).[15] A lower threshold can be interpreted as taking action at an earlier stage of time when a severe weather event is indeed likely to happen but there is still uncertainty as expressed by the probability of occurrence. Accordingly, a higher threshold can mean that people will take action later when a potential event is more likely to happen. In other words, a lower threshold can be interpreted as people being more risk-averse (they tend to avoid risk) and a higher threshold can be interpreted as people being more risk-taking or risk-seeking (see Morss et al., 2010; Ramos et al., 2013).[16]

Kox et al. (2015) noted that their specific user group of emergency services was very heterogeneous and differed with regard to requirements and needs (e.g. lead times), perceptions (e.g. of risk and uncertainty), level of weather-related knowledge and understanding (e.g. meaning of numerical forecasts), and legal and institutional constraints. Yet, if there is a diversity in capacity even within such a sophisticated group, the same – or an even larger – heterogeneity might apply for a much broader user-groups such as the general public (NRC, 2006).

In this context risk is seen as a 'multi-dimensional construct' (Wiedemann and Schütz, 2010, p. 799). Risk perception is not only dependent on the characteristics of the hazard

[15] This economic perspective, however, does not apply to situations where monetary damage costs are difficult to assign, like loss of life or social or political reputation. In other situations, people might want to act, but do not have the ability to do so, due to professional constraints or limited resources.

[16] Beside this interpretation a higher threshold can also mean that someone is less willing to take any action based on a probability forecast.

(magnitude or severity, probability, duration, areal extent), but also on other factors that characterize the threat, such as the hazard source, possible consequences (i.e. damage costs) or the situation of the respective person (Burton et al., 1993). A number of different approaches have been applied in social science risk research to address risk perception and risk-reduction behaviour (for further discussions see, e.g. Bubeck et al., 2012; Renn et al., 2007; Werg et al., 2013). Varying influencing factors are addressed in the different studies. Examples are trust (e.g. Johnson and Slovic, 1995; Siegrist, 2001), hazard experience (e.g. Bubeck et al., 2013; Mileti and Sorensen, 1990; Silver and Andrey, 2014), self-efficacy (e.g. Bubeck et al., 2013; Grothmann and Reusswig, 2006), or socio-demographic and socio-economic variables such as gender, age, income, education level, or home ownership (e.g. Biernacki et al., 2008; Grothmann and Reusswig, 2006; Mileti and Sorensen, 1990; Siegrist and Gutscher, 2006; Silver, 2015).

Wachinger et al. (2013) showed the complex relationship between risk perception and actual response in the case of natural hazards. Based on a review that also included multidisciplinary studies on natural hazards, they negate the general assumption that individuals with low risk perception are less likely to respond to warnings and to undertake preparedness measures than individuals with high risk perception. They derive three possible reasons for the relationship between risk perception and protective action: first, experience and motivation, second, personal ability to act, which is constrained by economic and personal conditions, and third, trust and responsibility. Likewise, Demuth et al. (2011) discuss the importance of including individual attitudes and behaviours in the analysis of people's use and perception of weather forecasts.

Although there is a large body of literature on risk perception and protective behaviour (e.g. Kahneman and Tversky, 1979; Kunreuther, 1996; Palm, 1998; Rogers, 1983), comparatively little is known about the decision thresholds that numerical weather forecasts must exceed in order to trigger protective behaviour and how these are influenced (for exceptions, see Joslyn and Savelli, 2010; Morss et al., 2010). Therefore, this paper focuses on the question whether there are influencing factors that determine decision thresholds for numerical weather forecast information at which the general public would start protective action. A scenario was created in a questionnaire survey (design see 3.2.2) in order to a) determine individual decision thresholds[17] and b) test whether subgroups of the sample – determined by different influencing factors such as age, gender, hazard experience or ability to act – lead to different thresholds. The idea stems from a scenario-based study with participants of an US nationwide survey published by Morss et al. (2010). They asked at which forecast probability of a temperature below freezing people would decide to cover their garden plants. They concluded that *"different individuals have different percentage-chance thresholds for decision making based on their risk tolerance, the context, and other factors"*(p. 158). Like in the US, temperature forecasts in Germany are usually not accompanied by uncertainty or probability information, raising the question whether this has an effect on the general public's decision to act. In the present study, the scenario was altered to incorporate the variable 'value of property at risk' in order to discuss the relevance of the damage (costs) caused by the weather.

The following research questions are derived from these considerations:

Research question 1: Is people's willingness to perform protective actions affected by a) the severity of the expected weather event, and b) the value of the property at risk?

Research question 2: Is the probability threshold for taking protective action affected by a) the severity of the expected weather event, and b) the value of the property at risk?

Research question 3: Do individual experience, motivation, trust, personal ability to act and structural determinants like socio-economic and socio-demographic variables affect the probability thresholds?

The following sections describe the questionnaire with the scenario design, the outcome variables and factors for the analysis, and the sample characteristics of this survey (Section 3.2). Later sections address the results (Section 3.3), discuss the main findings and limitations of this study (Section 3.4), and draw conclusions (Section 3.5).

[17]Note that we are not searching for an absolute threshold number, but rather analysing the relation between the different scenarios.

3.2 Methods

To investigate the probability threshold for decisions on protective action of the general public and factors that might influence such decisions, a questionnaire with a decision scenario was created and distributed among residents in Berlin, Germany, via an online–access–panel provider. The aim of the decision scenario was to identify a probabilistic threshold for forecast users to take protective action based on a hypothetical probabilistic weather forecast. In this section, the decision scenario will be outlined first, which is followed by the influencing factors addressed in the questionnaire. Finally, the data collection and sample characteristics will be outlined.

3.2.1 Weather Forecast and Decision to Act: The 'Garden Scenario'

The decision scenario consisted of four questions representing different sub-scenarios. The four questions were located in the middle of the questionnaire succeeding introductory questions about media use and weather communication and preceding questions such as experience with severe weather, confidence in forecasts and socio-demographic and social- economic characteristics (for further discussion, see 3.2.2). In the present survey, participants were asked to assume that they own a garden centre with some plants outside. The scenario continued with the information that a weather forecast for the coming night indicated a certain level of probability for frost. Participants had two major response options: they could either place back all plants in the greenhouse given a level of probability for frost or they could state that they would not place back the plants.[18] If participants chose the first response option, they were asked to specify the level of probability a forecast should indicate to make them take action, if they were relying exclusively on this weather forecast. The participants were allowed to type any

[18]Mylne (2002) notes that, if no forecast were available, a sensible forecast user would have two options: either always protect or never protect. A third way would be to act by chance, although this does not really qualify as a sensible option. One could add that experienced people would never totally act by chance as they would also include their own observations of the current weather situation in their decisions.

number between 0 and 100 in an open-space text box to specify the level of probability (for a detailed scenario design, see Appendix B).

This general scenario setting was altered resulting in four sub-scenarios (see Tab. 3.1) which differed in the key variables temperature and value of property at risk. All respondents received all four sub-scenarios in sequence and were asked the same questions. In the first scenario (or 'baseline scenario'), people were asked to make a decision about a forecast indicating slight frost (temperatures falling below 0°C). In the second scenario (or 'severe frost scenario'), the forecast was changed to severe frost (temperatures falling below -10°C).

Each of the two temperature scenarios was further altered by stating that the plants outside were of great value. Participants were asked again to make a decision on a forecast indicating slight frost ('valuable scenario'), or severe frost ('severe/valuable scenario'), respectively. Accordingly, the four sub-scenarios represented every possible situation within the variables of value of temperature and extent of value of property at risk (see Tab. 3.1). The decision scenario was pre-tested along with the rest of the questionnaire. Several other options were tested (moving an outdoor picnic indoors, taking a bicycle to work, taking an umbrella, going for a walk in the woods, etc.). However, pre-test results revealed that the garden-centre scenario and the forecast of frost were best understood by the test groups.

Table 3.1: Garden Scenario Characteristics

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Threat of frost	Slight (< 0°C)	Severe (< -10°C)	Slight (< 0°C)	Severe (< -10°C)
Property at risk	Unspecified	Unspecified	High value	High value
Scenario name	"baseline"	"severe frost"	"valuable"	"severe/valuable"

3.2.2 Influencing Factors

The decision thresholds as determined by the garden scenario might be influenced by several factors, which was explored by the questionnaire from different angles. Altogether 37 questions are discussed in this paper (see Appendix C): socio-demographic and social-economic characteristics such as gender, age, education[19] or housing status/ home ownership (9 questions), media use and prior experience with severe weather (5 questions), the ability to act, self-efficacy or locus of control (10 questions), trustworthiness of forecasters and confidence in weather forecasts (9 questions) and desire for certainty (4 questions). They were rated with two different types of items: self-rated 5-point Likert-type items that ranged from 1 (strongly disagree) to 5 (strongly agree) and multiple-choice items using a true–false scoring procedure. Participants could also respond “I do not know”. While some items were directly taken from the literature (Bandura, 1977; Rotter, 1954, 1966), most items were adapted from other studies (Johnson and Slovic, 1998; Kox et al., 2015; Morss et al., 2010). The reliability of scales was tested using Cronbach’s Alpha, which measures internal consistency of items within a scale. The acceptable range for α was set to $\geq$ 0.6. A scale has a high reliability if it produces similar results under consistent conditions (Crocker and Algina, 2008).

Hazard experience

Direct experience is linked to someone witnessing the disruptive effects of severe weather or being personally affected. When direct personal experience of a (disastrous) event is lacking, people can learn about a hazard from many indirect sources, including the media (Biernacki et al., 2008; Silver and Andrey, 2014; Smith, 1992). Direct experience was measured on a scale with 5-point Likert-typed items ($\alpha = 0.8$) which represents different levels of experience related to the (both geographical and personal) distance: direct personal affliction (item 1: *“How often have you personally been affected by severe weather events (heavy thunderstorms, hurricane-force gusts etc.) in Berlin over the past*

[19] As education does not necessarily have to correlate with knowledge about weather, participants were also asked multiple-choice questions (true–false) about weather-related terminology and behaviour (Keul and Holzer, 2013) and familiarity with severe weather alerts (Ripberger et al., 2015). Despite positive signals from the pre-test phase, the reliability analyses revealed that only one out of four questions met the requirements ($\alpha \geq$ 0.6).Therefore, this scale was not used for the further analysis. It is recommended that further studies add more questions regarding meteorological knowledge in the questionnaire in order to choose from a broader range of items.

12 months?"), witnessing of severe weather effects in the near neighbourhood (item 2: *"How often have you observed damages resulting from severe weather in your neighbourhood over the past 12 months?"*) and in the city (item 3: *"How often have you observed damages resulting from severe weather in Berlin over the past 12 months?"*). (The items were not weighted due to missing information about people's mobility.)

Following Smith (1992), indirect experience was measured by participants' access to forecasts. Participants were asked to state which source of information (television (TV), radio, websites, apps, etc.) they use and how often they retrieve weather forecasts (daily, several times a week, occasionally, only in preparation for outdoor activities, rarely or never).

Ability to act

There are several ways to measure people's perception of their own ability to act: the locus of control scale (Rotter, 1954, 1966) measures to which degree people believe they can control events which affect them. The scale consists of two subscales (internal and external) with two 5-point Likert-type items each. Internal locus of control refers to people's belief that they can control their personal life. External locus of control refers to people's belief that their life is controlled by fate or other external factors they cannot control. Second, self-efficacy (Bandura, 1977) measures people's individual belief that they can rely on their own competence if dealing with day–to–day difficulties (Hinz et al., 2006). For this study, an additional third scale was created to focus directly on the self-perceived ability to act on severe weather threats. Unlike the previous scales it is not taken directly from the literature. Instead the items were developed during the pre-test phase. The scale includes three 5-point Likert-type items ($\alpha = 0.6$) measuring people's belief in their own capability to protect themselves against severe weather (item 1: *"I personally have good options to promptly safeguard myself and my belongings against an imminent severe weather threat."*), their capability to inform themselves (item 2: *"I personally have good options to inform myself about imminent severe weather threats in time."*), and that gathering this information is one's own duty (item 3: *"It's up to me* *to inform myself independently and in time about imminent severe weather threats."*). While item 1 and 2 also tackle the issue of self-efficacy, item 3 mainly addresses the question whether people perceive themselves as being responsible for being informed about potentially damaging events.

The scale measuring self-perceived ability to act correlates significantly with self-efficacy ($r = 0.425, p < 0.001$), and internal locus of control ($r = 0.348, p < 0.001$). In this regard and for space considerations, only the results of the more specific ability to act scale will be presented in the results section below.

Confidence, trustworthiness, and desire for certainty

In risk perception and communication research, the distinction between confidence and trust has proven to be useful (Frick and Hegg, 2011; Luhmann, 2000; Siegrist and Cvetkovich, 2000; Siegrist, 2001). While trust refers to the reliability of the information source and the informant (Frick and Hegg, 2011; Ripberger et al., 2015), confidence refers to *"experience or evidence, that certain future events will occur as expected"* (Siegrist, 2001). In the latter case, any feelings of trust are non-existent (ibid.). Here, confidence in forecasts refers to people's belief in the reliability of a weather forecast.

Confidence in weather forecasts was measured by seven 5-point Likert-type items ($\alpha = 0.9$) ranging from 1 (very low) to 5 (very high). The scale includes an item representing a statement about general confidence in weather forecasts (item 1: *"How high is your general confidence in the accuracy of weather forecasts?"*) and correspondingly phrased statements about people's confidence in 2-day forecasts (item 2, 3 and 4; $\alpha = 0.8$) and 7-day forecasts (item 5, 6 and 7; $\alpha = 0.9$) of either temperature, chance of precipitation and amount of precipitation. The items representing different forecast lead times and content were adapted from Morss et al. (2008a).

Contrary to the question about confidence in a given forecast, the questions about trustworthiness, or more precisely about integrity (Mayer et al., 1995), aimed at people's views on the source of the (uncertain) information. This might be the national or regional meteorological service or the media in general. Uncertainty is a *"fundamental* *characteristic of weather"* (NRC, 2006). It is assumed that being open and transparent about uncertainty will enhance trustworthiness and confidence in the quality of scientific output (Johnson and Slovic, 1995). The items are loosely based on items by Johnson and Slovic (1998) who investigated lay people's views on environmental health risk assessments. They showed that the participants of their study consider the presentation of uncertainty as honest and competent. In the case of this study the question is, whether or not forecasts that contain uncertainty information are seen as signalling honesty, and thus as trustworthy, and have an effect on the decision to act. The scale consists of two Likert–scale–items ($\alpha = 0.6$) related to people's belief that non-deterministic information shows that the provider of such a forecast does not fully understand the situation and is trying to hide a lack of knowledge (item 1: *"If meteorologists were honest about the size of a hazard, they would not use probabilities but one unambiguous number."*; item 2: *"Probabilities in weather forecasts are used in order to hide lack of knowledge, because the situation could not be entirely apprehended."*). Note the negative direction of the scale: the higher the values, the lower the trust.

In their study, Johnson and Slovic (1998) also found that people want to be provided with probabilistic information and do not have a 'desire for certainty' or demand deterministic information. For this study, the items used in the study by Johnson and Slovic (1998) were been adapted for weather risks. Here, the 'desire for certainty' scale ($\alpha = 0.7$) included people's rejection of probabilistic information and a preference for deterministic information (item 1: *"If severe weather is likely to happen, I do not want to hear assumptions or speculations. I want to know whether it will occur or not."*), their preferences for expert opinions instead of self-assessments (item 2: *"I want experts to tell me whether or not I am threatened by severe weather instead of having to draw my own conclusions from the information available."*), their opinion that weather forecasts have to be deterministic (item 3: *"A professional and reliable weather forecast uses single and concrete numbers."*) and that warnings are always aligned with high risks (item 4: *"Weather warnings are only issued when there is a high risk for the people affected."*).

3.2.3 Data Collection, Sample Characteristics and Data Analysis

The whole questionnaire was written in German and pre-tested with 23 scientists and students from Freie Universität Berlin in March 2014. Between 28 April and 13 May 2014 a total of 1405 residents of Berlin, Germany (aged 18 to 90) were recruited through an online– access–panel provider to participate in an online survey. 63 'speeders' (people answering the questionnaire in less than 1/3 of the overall median time of approximately 15 min) were excluded, leaving a total of 1342 completed questionnaires.

A summary of the sample (Tab. 3.2) reveals broad similarities to the Berlin census data (AfS, 2012a,b; Destatis, 2013), with the exception that the study sample has a higher number of participants that have been resident in Berlin for more than ten years and shows slightly higher levels of education. The sample has a very high percentage of tenants, which is typical for Germany, especially for Berlin. Although most people live in multi-family houses (30.5 %) or in apartment buildings (41.6 %), a majority state that they have a balcony (66.5 %) or a garden (29.5 %). This issue will be discussed in more detail at a later point of this paper.

Table 3.2: Socio-Demographics of the Study Sample (n = 1342) in Comparison to the Berlin Census Data (Sources: AfS 2012a *, AfS 2012b **, Destatis 2013 ***)

	Study sample	Census data Berlin
Gender (%, women)	48	51 *
Age (median)	35–44	35–44 *
Household income (median, monthly)	1000 € – 2000 €	1500 € – 2000 € *
Education (%, college entrance qualification)	56	35.2 *
Mobility status (%, resident > 10 years in Berlin)	77.4	40.9 **
Housing status (%, tenancy)	82.1	84.4 ***

The weather conditions during the survey period were calm and temperatures were unremarkable for the season. No frost occurred. However, the participants should be used to frost, as Berlin usually experiences temperatures below 0°C on half of the winter days. No extraordinary low temperatures occurred during the winter of 2013/2014 before the survey.

The data analysis was performed using SPSS 22, software used for statistical analysis in social science. The analysis included calculations of relative frequencies, cross tabulations and comparisons of means. Statistical significance was determined using analysis of variance (ANOVA) as well as Kruskal-Wallis test and Friedman test among repeated measures as non-parametric models. Post–hoc–tests were performed using Dunn-Bonferroni pairwise comparisons. For a binary response Cochran's Q test was used. Non-parametric tests were used if the sample was not normally distributed and thus did not meet the necessary assumptions for parametric tests. Normality of the sample was tested via visual inspection of the histograms and measuring skewness and kurtosis of the distribution. If either score divided by its standard error is greater than $\pm$ 1.96, it suggests that the sample is not normally distributed (Cramer, 1998; Doane and Seward, 2011). The analysis of the decision scenario was split into two parts. First, frequencies of the two major response options of each scenario as stated above were calculated in order to determine people's willingness to act. Second, the mean probability thresholds for each scenario were calculated for people who were willing to act.

3.3 Results

With regard to the three research questions posed in the introduction, the results of the survey will be presented as follows: First, we look at willingness to act and general decision thresholds as addressed in the research questions 1 and 2. Finally, we look at the influence of the factors (as described in Section 3.2.2) on the probability thresholds as addressed in research question 3.

3.3.1 Willingness to Act and General Decision Thresholds

Results show that 306 out of 1342 people (22.8 %) stated that they would not act based on the slight frost forecast in the described situation of the 'baseline scenario' (see Fig. 3.1). The mean threshold of the remaining 1036 is 46.4 % probability for frost (standard deviation (SD) = 24.4). The number of people not willing to act is reduced to 160 (11.9 %)

if severe frost is forecasted (scenario 2). Here the mean threshold of the remaining 1182 participants is 38.8 % (SD = 29.7). 310 (23.1 %) would not act, if the forecast indicates slight frost but the plants at risk are of higher value (scenario 3). The mean decision threshold for this scenario is 39.9 % (SD = 26.6, n = 1032). The number of non-action is again reduced in the 'severe/valuable scenario' to 169 (12.6 %) if severe frost is forecasted and valuable plants are endangered. Here, the mean decision threshold is 35.7 % (SD = 30.5, n = 1173). Across all scenarios 128 participants (9.5 %) chose not to act in any of the four scenarios, while 98 participants (7.3 %) chose not to act in scenarios 1 and 3 (less severe events) and only 4 participants (0.3 %) chose not to act in scenario 2 and 4 (more severe events).

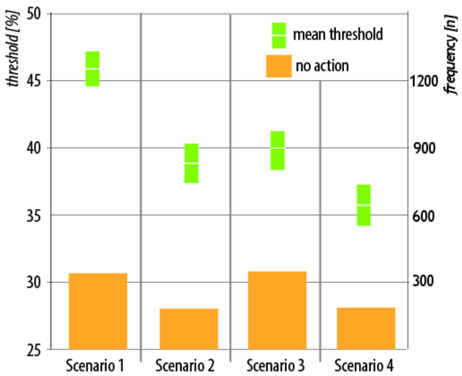

Figure 3.1: Number of Participants Choosing Not to Act and Probability Threshold for Action with 95 % CI for each Scenario (Scenario 1: Slight Frost; Scenario 2: Severe Frost; Scenario 3: Slight Frost, High Value; Scenario 4: Severe Frost, High Value; see Tab. 3.1); compiled and designed by author

Concerning research question 1, it is striking that more people decided to act in the scenarios involving a more severe weather threat (scenarios 2 and 4) than in the other. A Cochran's Q test determined that there was a significant difference among the four sub-scenarios ($\chi^2 = 268.93$, df = 3, $p < 0.001$). With regard to research question 2, mean thresholds are lower in all scenarios involving either severe weather or property of special value (no. 2 to 4) compared to the initial 'baseline scenario'. A non-parametric Friedman test of differences among repeated measures was conducted and rendered a Chi-square value of 712.5 which was significant ($p < 0.001$). Additionally, probabilities in scenarios involving severe frost (no. 2 and 4) scatter slightly more (i.e. have higher standard deviations), indicating that people answered less consistently in these scenarios. The implications will be further discussed in Section 3.4. The following sub-section show the results with regard to research question 3.

3.3.2 Influence of Socio-Demographic and Socio-Economic Variables on the Decision Threshold

Education was measured by people's highest degree level and grouped following the German school system into low education level (no secondary school graduation and lower secondary education), mid education level (secondary education without college entry qualification) and high education level (upper secondary education with college entry qualification). Results show that people with higher education are more likely to state a lower threshold of probability that makes them to take protective measures than people with lower education. Education had a significant effect on thresholds involving severe frost no. 2 and 4 (Kruskal-Wallis test, scenario no. 2: $\chi^2 = 32.205$, df $= 2$, $p < 0.001$; no. 4: $\chi^2 = 41.659$, df $= 2$, $p < 0.001$)[20], but no significant effects on the two other. A post–hoc–test using Dunn-Bonferroni pairwise comparisons revealed significant differences between high education and middle education ($p < 0.001$) and high education and low education ($p < 0.001$) for the 'severe frost scenarios' (2 and 4), and significant differences between middle education and low education ($p = 0.043$) for scenario 4. Please note that education is slightly correlated with other socio-demographic and socio-economic variables, namely income ($r = 0.218$, $p < 0.001$), age ($r = 0.161$, $p < 0.001$) and housing status ($r = -0.167$, $p < 0.001$, meaning more educated people tend to own a house rather than rent it).

A one-way ANOVA yielded no significant effect of gender on the mean thresholds in the four scenarios. Generally, the relationship between gender and protective action is highly context dependent and often unclear (for further discussion see, e.g. Silver and Andrey, 2014; Werg et al., 2013).

[20] All means and standard deviations for all four scenario thresholds are presented in Appendix D.

Age had a significant effect on thresholds in the 'severe frost scenario' (Kruskal-Wallis test, scenario no. 2: $\chi^2 = 16.784$, df = 5, $p = 0.005$) but no significant effects on the other scenarios. A post–hoc–test revealed significant differences between the age group 18 to 24 years and 55 to 64 ($p = 0.007$) for scenario 2, but no significant differences between the other age groups in this scenario. In the 'severe frost scenario' thresholds drop to 30.9 % in the group aged 18 to 24 years, and increases to 44 % in the group aged 55 to 64.

Housing status had a significant effect on thresholds in all but the 'valuable scenario' no. 3. (Kruskal-Wallis test, scenario no. 1: $\chi^2 = 3.974$, df = 1, $p = 0.046$; no. 2: $\chi^2 = 4.89$, df = 1, $p = 0.027$; no. 4: $\chi^2 = 4.524$, df = 1, $p = 0.033$). Tenants are more likely to state a higher threshold in these scenarios than homeowners. Participants were also asked if they have a garden or a balcony. Results show a significant effect of having one or none of them on the mean thresholds in all but the 'baseline scenario' (ANOVA, scenario no. 2: $F_{1,1180} = 9.049$, $p = 0.003$; no. 3: $F_{1,1030} = 3.888$, $p = 0.049$; no. 4: $F_{1.1171} = 6.669$, $p = 0.01$). Having either a garden or balcony leads to higher decision thresholds (Fig. 3.2).

The effect of urban settings, like housing status or housing type, on risk perception and protective action has been widely discussed in the literature (Biernacki et al., 2008; Burton et al., 1993; Wachinger et al., 2013). In contrast to most privately owned rural houses, urban houses like apartment buildings and tower blocks are much more difficult to individually secure against weather events as the owner's permissions is often required to make adjustments. Therefore, homeowners are more sensitive to natural hazards than tenants, and rural dwellers are more likely to protect their homes than their urban counterparts (Biernacki et al., 2008; Burton et al., 1993; Grothmann and Reusswig, 2006). This is consistent with findings in the present study as results show that tenants stated higher thresholds in the scenarios involving more severe frost (scenarios 2 and 4) than people who own their houses.

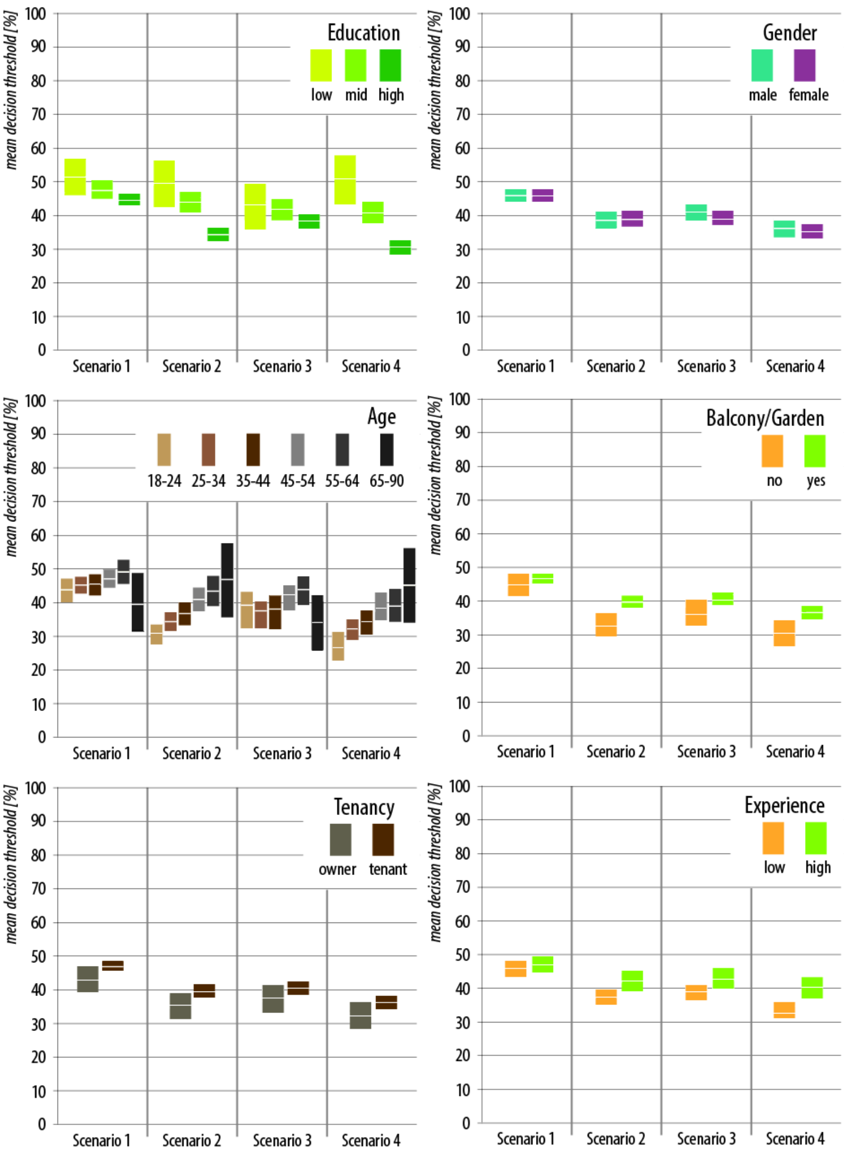

Figure 3.2: Mean Threshold of Socio-Demographic and Socio-Economic Variables for all four Scenario Thresholds: a) Education, b) Gender, c) Age, d) Possession of Garden and/or Balcony, e) Tenancy/Housing Status, and f) Direct Experience (95 % CI); compiled and designed by author

3.3.3 Influence of Hazard Experience on the Decision Threshold

Results show that the participants in general stated low to medium direct experience with severe weather (personal affliction, item 1: mean = 2.17, SD = 0.88; neighbourhood, item 2: mean = 2.13, SD = 0.91; within city, item 3: mean = 2.54, SD = 0.92). Statements have been grouped in two bins (low experience, high experience) separated by using the median of the data (low experience: n = 655, 48.8 %; high experience: n = 447, 33.3 %; missing: n = 240). Direct experience had significant effects on thresholds in scenarios involving severe frost no. 2 and 4 (Kruskal-Wallis test, scenario no. 2: $\chi^2 = 4.859$, df = 1, $p = 0.028$; no. 4: $\chi^2 = 10.133$, df = 1, $p = 0.001$). Results show that the higher the level of direct experience, the higher is the decision threshold in all scenarios (Fig. 3.2).

With respect to media use, 69.4 % of the participants stated that they use weather forecasts daily and further 23.3 % use them several times a week. 80.6 % of survey participants stated that they use TV as one source of information, followed by radio (61 %), internet websites (60.9 %), apps (58.1 %) and daily newspapers (23.5 %). Only 5.3 % use SMS or e-mail notifications. Hence, traditional mass media are still the primary source of weather information. A matter noted as well in other studies (Biernacki et al., 2008; DWD, 2006). However, in contrast to direct experience, results show no significant effect of indirect experience on decision thresholds: neither frequency of media use, nor usages of different media sources alter decision thresholds significantly.

Hazard exposure of property and direct experience of severe weather events (either first-hand or passed on by family or neighbours) can lead to an increased awareness and improve general protective behaviour (Biernacki et al., 2008; Bubeck et al., 2013). However, there are also examples for the opposite effect: *"low severity and seldom experienced events can produce a false sense of security/ misjudgement of ability to cope. [...] individuals who had previous experience with a hazard event and who did not experience personal damages are more likely to believe that a future event will unlikely affect them and, therefore, their risk perception decreases"* (Wachinger et al., 2013, p. 1052). In addition, awareness does not necessarily have to be translated into behaviour that would otherwise be anticipated (Biernacki et al., 2008).

Indirect experience (media use) had no significant effect on any decision threshold in this study. This is consistent with findings from other studies (Biernacki et al., 2008). In this case, it might partly be due to non-differentiating results: nearly 70 % of the participants use weather forecasts daily and over 90 % use them more than once a week. Furthermore, people use all kinds of media sources and only few rely on TV or radio, or on websites and phone apps alone. As Siegrist and Gutscher (2006) pointed out, media coverage is not that important if someone has had direct experience with the hazard in the past. Since frost is not an unusual weather event in the study area, it can be assumed that people are familiar with the hazard to a certain extent. Of course this would change if someone faced an unfamiliar hazard.

3.3.4 Influence of Self-Perceived Ability to Act on the Decision Threshold

For the analysis, the continuous self-perceived ability to act scale has been grouped into four bins (width: one standard deviation): very low (relative frequency of values: 14.5 %), low (34.4 %), high (32 %), and very high (19 %). People's self-perceived ability to act had a significant effect on the decision thresholds in all but the 'baseline scenario' (Kruskal-Wallis test, scenario no. 2: $\chi^2 = 8.719$, df $= 3$, $p = 0.033$; no. 3: $\chi^2 = 8.612$, df $= 3$, $p = 0.035$; no. 4: $\chi^2 = 12.035$, df $= 3$, $p = 0.007$). The higher the self-perceived ability to act the lower is the decision threshold (Fig. 3.3). A post-hoc test revealed significant differences between very low and very high levels of ability to act for scenario 2 ($p = 0.035$), scenario 3 ($p = 0.043$) and 4 ($p = 0.004$) and significant differences between very low and low in scenario 4 ($p = 0.049$). That there are no significant differences for the baseline scenario suggests that ability to act does not matter much in everyday situations, but becomes important when event severity and value of the property at risk increases. In this situations (scenarios 2–4), people with a very low level of self- perceived ability to act report consistently higher thresholds for action, reflecting their lack of efficacy. In contrast, people with higher levels of self-perceived ability to act report consistently lower thresholds for action, reflecting their efficacy when a risk of any level is posed. This becomes most explicit in scenario 4, where all but the people with very low level of ability to act report lower thresholds for action, suggesting that most groups would act in the riskiest of situations.

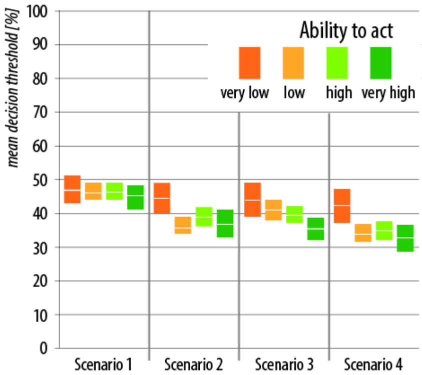

Figure 3.3: Mean Decision Thresholds for Self-Perceived Ability to Act on all four Scenario Thresholds (95 % CI); compiled and designed by author

High self-perceived ability to act or self-efficacy seem to be important drivers for protective action. This can be linked to the fact that protection measures in case of meteorological hazards are mostly individual in nature and generally refer to protecting oneself or to protecting moveable items securing objects on the balcony or moving them indoors, moving cars to safer places or avoiding staying outdoors (Kox, 2015). Likewise, Biernacki et al. (2008) found that people see storm protection measures, in contrast to flood protection, as their own responsibility rather than that of the government, as most wind protection measures were seen as much more of individual nature. In order to develop adequate warnings it is of great importance whether people see the responsibility for protection as lying in their own hands or in the hands of others like the government (Wachinger et al., 2013).

3.3.5 Influence of Confidence, Trustworthiness and Desire for Certainty on the Decision Threshold

In general survey participants correctly expressed more confidence in 2-day temperature forecasts (mean = 3.83, SD = 0.78) than in 2-day forecasts of chance of precipitation (mean = 3.43, SD = 0.82) or amount of precipitation (mean = 3.08, SD = 0.86), as *"precipitation tends to be more challenging to forecast than temperature due to its greater spatial and temporal variability"* (Morss et al., 2008a, p. 979). Likewise, they correctly judged 2-day forecasts as more accurate (or more skilful) than 7-day forecasts (Balzer, 1994; Murphy and Brown, 1984) by expressing less confidence in longer lead time forecasts (7-day temperature forecasts, mean = 2.86, SD = 0.93; 7-day chance of precipitation forecasts, mean = 2.5, SD = 0.91, 7-day amount of precipitation forecasts, mean = 2.33, SD = 0.94). However, people's confidence in forecasts had no significant effect on decision thresholds in all four scenarios. Neither the overall confidence in forecast scale, nor the general confidence in weather forecast item (item 1), nor confidence in 2-day forecasts (item 2, 3 and 4) revealed significant effects. In contrast, trustworthiness (related to the use of non-deterministic information) had a significant effect on thresholds in all four scenarios (Kruskal-Wallis test, scenario no. 1: $\chi^2 = 22.174$, df = 4, $p < 0.001$; no. 2: $\chi^2 = 44.502$, df = 4, $p < 0.001$; no. 3: $\chi^2 = 26.425$, df = 4, $p < 0.001$; no. 4: $\chi^2 = 58.130$, df = 4, $p < 0.001$). The higher the trustworthiness, the lower the decision thresholds in all four scenarios (Fig. 3.4). A post hoc test revealed significant differences in scenario 2 between mid and low trustworthiness ($p = 0.003$) and mid and very low ($p = 0.001$) and in scenario 3 between mid and low ($p = 0.02$) and mid and very low ($p = 0.015$), and in scenario 4 between very high and very low ($p = 0.021$), high and very low ($p = 0.005$), mid and low ($p = 0.005$) and mid und very low ($p < 0.001$). Additionally, there is a significant correlation between trustworthiness and education ($r = -0.343$, $p < 0.001$; higher education, less distrust[21]). Although the expression of confidence in weather forecasts is not directly related to the level of knowledge about forecast uncertainty, it can give an idea about people's perception of weather forecasts and their understanding of the inherent uncertainty (NRC, 2006). It can be assumed that there is also a link between trust and the level of knowledge about risks: Most people do not have the knowledge needed for a rational risk assessment associated with most complex situations (like weather conditions). They therefore rely on expert assessments (like weather forecasts and warnings). However, if self-knowledge

[21] Please keep in mind the negative direction of the trustworthiness scale.

is perceived as being adequate to assess the risks, people will make their own judgements (Siegrist and Cvetkovich, 2000). The less knowledge someone has about a risk (and its embedded uncertainty), the less he/she trust in his/her own personal judgement and the more he/she trusts the advice of authorities and their appraisals of the situation (Luhmann, 2000; Siegrist and Cvetkovich, 2000).

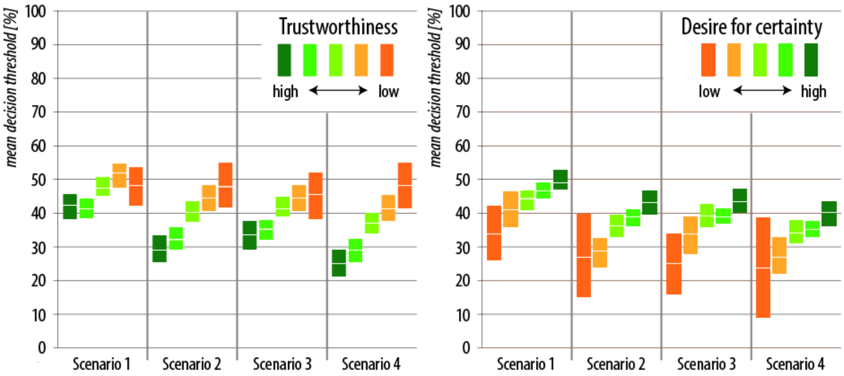

Figure 3.4: Mean Decision Thresholds for a) Trustworthiness, and b) Desire for Certainty on all four Scenario Thresholds (95 % CI); compiled and designed by author

Similarly, people's desire for certainty had a significant effect on thresholds in all four scenarios (Kruskal-Wallis test, scenario no. 1: χ^2 = 16.268, df = 4, $p < 0.005$; no. 2: χ^2 = 17.8, df = 4, $p < 0.005$; no. 3: χ^2 =12.995, df = 4, $p < 0.05$; no. 4: χ^2 = 16.289, df = 4, $p < 0.005$). The higher the desire for certainty is, the higher the decision thresholds are (Fig. 3.4). A post hoc test revealed significant differences in scenario 1 between very high and very low (p = 0.001) very high and low (p = 0.007) and high and very low (p = 0.019), in scenario 2 between very high and high (p = 0.04), very high and low ($p < 0.001$), very high and very low ($p < 0.001$), high and low (p = 0.039), high and very low ($p < 0.001$), in scenario 3 between very high and low ($p < 0.001$), very high and very low ($p < 0.001$), high and low (p = 0.039), high and very low (p = 0.023), and in scenario 4 between very high and high (p = 0.015), very high and low ($p < 0.001$), very high and very low ($p < 0.001$), high and low (p = 0.02) and high and very low ($p < 0.001$). One possible explanation is that some people may prefer being told what to do and whether a situation is safe or unsafe, as uncertainty may disturb them (Johnson and Slovic, 1995). Therefore, it is not surprising that people who have a strong desire for certainty act when the weather forecast is comparatively more unambiguous and clearer in their opinion.

3.4 Discussion and Limitations

This paper focuses on whether it is possible to identify thresholds of numerical weather forecasts at which the public would start protective action, and whether the decision to act is influenced by the severity of the event, the value of property at risk or other influencing factors. Firstly, the results show that people's willingness to act tends to be higher, the more severe the forecasted weather event is. This supports the first part of the first research question stated in the introduction. Most people seem to have a good sense for threat of frost and it is therefore not surprising that they are more likely to act in severe frost scenarios, as the likelihood for potential damage to the plants rises, the lower the temperatures drop. This general outcome illustrates that the surveyed people understood the scenario, created valid data and thus enabled the consequent investigations on what factor influence the decision threshold. Secondly, mean decision thresholds tend to be lower in scenarios involving either severe weather or property of higher value (no. 2 to 4) compared to the low threat/low value 'baseline scenario' (no. 1). These findings support the second research question. A lower threshold can be interpreted as taking action at an earlier stage when a severe weather event is indeed likely to happen but there is still uncertainty as expressed by the probability of occurrence. On the other hand, a higher threshold can mean that people will take action later when a potential event is more likely to happen. In other words, a lower threshold can be interpreted as people being more risk-averse (i.e. they tend to avoid risk), and a higher threshold can be interpreted as people being more risk-taking or risk-seeking (e.g. Morss et al., 2010; Ramos et al., 2013).

Several of the presented factors have a significant effect on the mean decision thresholds, thus, supporting parts of research question 3. While some socio-economic or socio-demographic determinants such as gender had less or no effects, education and housing status on the other hand had strong effects on scenarios involving more severe frost. Homeowners tend to be more risk-averse than people who rent their homes. These findings are in accordance with the relevant literature as homeowners generally tend to be more sensitive to natural hazards than tenants and show more self-protective behaviour (e.g. Biernacki et al., 2008; Burton et al., 1993; Grothmann and Reusswig, 2006). Whereas tenants might tend to choose moving to a safer place as risk-avoiding behaviour as indicated by Thieken et al. (2007) for flooding. As the survey took place solely in the urban settings of Berlin, differences in risk perception between rural and urban dwellers could not be addressed.

In the scenarios involving more severe frost, people with higher levels of education tend to be more risk-averse than people with less education. It might be that they are more aware of the potential consequences of a frost hazard. But this argument misses the possibility that graduation from school does not necessarily have to correlate with general meteorological knowledge or numeracy skills. Further work should address these issues separately (i.e. with individual items or scales) in order to get a more detailed picture.

In addition, people who have the experience of regularly exposing property to weather hazards (since they have access to a garden, a balcony or both) and people who stated higher experience with severe weather tend to be more risk-seeking. At a first glance, this result comes at a surprise. One possible explanation might be that hazard experience and ownership of a garden/balcony led to the implementation of precaution measures, which leads to a more risk-seeking behaviour as people feel more secure. Furthermore, constant confrontation with the consequences of frost might contribute to a better familiarity with the hazard and people think that they are more competent and therefore act more risk-seeking. However, it has to be noted that experience was measured with more general disruptive weather events like thunderstorms and hurricane-force gusts, which does not necessarily have to match with experience of frost.

Overall, a high level of self-perceived ability to act or self-efficacy seem to be important drivers for protective action. But some questions remain: What are the reasons for low self-efficacy in this domain, and how can weather warnings better be addressed to these people?

A further interesting result is the allocated level of honesty or integrity[22]. of the provider of weather information regarding forecast uncertainty. Although stating uncertainty information is generally not perceived as dishonest by the majority, some people see it as such. Those people tend to be more risk-taking (stating higher decision thresholds). This is consistent with the findings that low probability is often seen as preliminary rather than complete information and lower risk numbers are seen as either less accurate or less honest (Johnson and Slovic, 1995). Or, as Patt and Schrag (2003) state, some people might believe that forecasts for extreme events are exaggerated in both probability and severity. This can lead to the problem that the perceived urgency for protective action is reduced when it is most important (Joslyn and Savelli, 2010).

Individual risk perception is not solely tied to objective criteria like the magnitude and frequency of a hazardous event; instead it is also based on individual experience, sensation, motivation, socialization and cultural background (Renn et al., 2007). Therefore, laypeople's understanding of the role of uncertainty in 'good science' might lead them think differently about risks than experts (Johnson, 2003). When communicating forecast uncertainty, it is important to understand that the forecasts users do not appear as a homogeneous group (Demuth et al., 2011; Kox et al., 2015; Silver and Conrad, 2010) and *"no single representation suits all members of an audience"* (Spiegelhalter et al., 2011, p. 1399). It is therefore recommended to use uncertainty information in weather forecasts, as it allows *"users to tailor the forecast to individual risk tolerances"* (Joslyn and Savelli, 2010, p. 181).

Still, there are some common limitations when using such a scenario in a questionnaire survey: All respondents were asked the same questions and received all four sub-scenarios in sequence. The questions were not randomised to control for order effects. Note that the scenario describes a fictional situation and the participants had only the choice whether or not to relocate the plants, but could not choose an adjustment measure such as purchasing insurance, using heating equipment, or providing shelter. Furthermore, the hypothetical

[22]Note that there are more dimensions of trust which are not addressed here. For further discussion see, e.g. Mayer et al. (1995)

scenario suffers from a lack of real consequences (e.g. losses) for the decisions and people might be less risk-seeking in real-life decisions. Such aspects may best be addressed using a real-life environment and studying real-life decision making (resulting in real-life consequences) using ethnographic research approaches such as observations. Professional users of weather information such as road maintenance crews, renewable energy operators or emergency services might be appropriate target groups for such an investigation.

3.5 Conclusion

This paper showed that when making decisions on protective behaviour the severity of an event and the value of the property at risk, or in other words the consequences of not taking actions, alter the decision thresholds significantly. The results show that people's willingness to act tends to be higher and mean decision thresholds tend to be lower (indicating risk-averse behaviour) in scenarios involving more severe weather or high value property. Additionally, the thresholds are influenced by different factors based on socialization and cultural background such as individual experience, education, housing status and ability to act, whereas classic socio-demographic determinants alone are often not sufficient to fully grasp risk perception and protection behaviour. Please note that the factors discussed here are not meant to provide an exhaustive list of the many other factors that may affect protective action. Such an analysis would be beyond the scope of this work.

Weather services should recognise that the public is not a homogeneous group of end-users. It is therefore recommended to communicate the uncertainty inherent in weather information so that users can tailor the forecast to individual risk tolerances. Wherever possible this should be an integrative and transdisciplinary process involving provider and user of the information, as it might be difficult to assess such risk tolerances. Furthermore, such a discussion would enable the weather services to recognise specific regional weather features and individual capabilities, and, overall, might contribute to a deeper understanding of numerical weather information.

4 Anticipation and Response. Emergency Services in Severe Weather Situations in Germany

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4.1 Introduction

Hydro-meteorological processes are the most common causes of natural hazards like storms and floods in Germany (GDV, 2016). Primarily impact refers to a loss of life and injuries, damage to the environment, infrastructure, and private property, often followed by secondary effects like psychological trauma, or disruption of workflow and traffic. Mitigation and prevention measures are generally summarized under the term 'disaster risk management'. The United Nations International Strategy for Disaster Reduction (UNISDR) defines disaster risk management as a *"systematic process of using administrative directives, organizations, and operational skills and capacities to implement strategies, policies and improved coping capacities in order to lessen the adverse impacts of hazards and the possibility of disaster"* (UNISDR, 2009, p. 10). Measures include *"land-use controls, insurance, engineered protection works and construction standards, disaster response plans, and emergency warning systems"* (Mileti and Sorensen, 1990, p. 1). The disaster management cycle represents a systematic approach to dividing the risk management process (Alexander, 2000; Dikau and Weichselgartner, 2005; Weichselgartner, 2002). TThis widely used concept in the emergency management community is adopted by various organizations for different hazards. The cycle describes successive phases of post- and pre-disaster situations that a society would undergo and the measures that emergency management would need to take in order to improve resilience and mitigate the impacts of natural hazards. The phases are not clearly distinguished from each other, but overlap from time to time. Additionally, any post-disaster measures are essential parts of a pre-disaster situation, as the circular pattern implies. The number of phases and the terminology differ, but most authors suggest three to four phases (e.g. Alexander, 2000; Dikau and Weichselgartner, 2005; Edwards, 2009). In this article, we follow Dikau and Weichselgartner (2005) and distinguish between pre-disaster mitigation and post-disaster emergency management. Mitigation includes short- and medium-term measures of preparedness and medium- and long-term measures of prevention. Emergency management, during or shortly after an event, includes measures of response and recovery. The response phase is characterized by emergency relief and rescue measures to cope with or limit impacts. The recovery phase focuses on measures for reconstruction and restoration. To lessen disruptive impacts, both the public and governmental authorities, that is, the emergency management services, take different adjustment measures. The distinction between pre-disaster mitigation and post-disaster emergency management is used here to understand different theoretical perspectives and as a guideline for the analysis of the qualitative data generated from this study.

4.1.1 Anticipation of Future Hydro-Meteorological Events

Pre-disaster mitigation measures always have an anticipatory component. The aim is to *"get hold of something which has not (yet) happened"*(Neisser and Runkel, 2017, p. 170). Anticipation is therefore a central concept of risk (Anderson, 2010; Hutter, 2010). Anderson (2010) focuses on three types of anticipatory action concerning risk: precaution, pre-emption and preparedness. While precaution is a rather regulatory concept and can be understood as a preventive logic used in, e.g. environmental law and spatial planning after the identification of a threat and before any harm occurs (Goede and Randalls, 2009; Klinke and Renn, 2002), the logic of pre-emption can be understood as *"prevention based on suspicion"* (Suskind, 2007). The latter is a logic where a one-percent chance of harm must be treated as a certainty in a potential high-magnitude, low-probability future where you cannot wait until a threat materializes, where firm evidence – of either intent or capability – is too high a threshold (Anderson, 2010; Daase, 2011; Suskind, 2007). Finally, preparedness involves measures during the propagation of effects or impacts of an event through the *"development of capabilities and resiliences that will enable response"* (Anderson, 2010, p. 792). According to the disaster management cycle, phases of response and recovery are strongly connected with the stated types of pre-disaster mitigation. The most significant articulation of response remains the formalized emergency services, that is, fire fighters (Anderson, 2016).

We will argue that in the case of severe weather, in addition to mitigation measures and the removal of damages (for example, broken trees, water damage), the main aim of actions taken by civil protection and emergency services is to maintain their ability to respond. In order to anticipate disruptive severe weather events, they have to be *"articulated, measured and detected as a risk"* (O'Grady, 2015, p. 133). Emergency services need to be aware of the situation and thus need information about the potential threat before it manifests. Delays in response are a main matter of concern (Anderson, 2016) and weather forecasts may become a highly relevant source for preparing action. In this context, several authors stress the importance of (lead) time. They see the main goal – and simultaneously the major challenge – of warnings as obtaining command over the time factor, which highly depends on the length of forewarning or lead time (see Clausen and Dombrowsky, 1984; Drabek, 1999; Hoekstra et al., 2011).

n order to lessen the impacts of disruptive events, *"a range of practices have been invented, formalized and deployed for knowing futures"* (Anderson, 2010, p. 783). In terms of hydro-meteorological hazards, weather forecasts are one way to anticipate the future development of the atmosphere (Fine, 2007) and, with respect to certain phenomena, give hints about potential events like thunderstorms, extreme wind or floods. (Weather) forecasts must be distinguished from warnings and alerts. While forecasts are a prognosis of future developments, warnings carry a certain message that increasingly indicates potential impact and gives guidance for adequate response. Alerts are just wake–up–

calls. A warning without a context (about a specific hazard, a location and time, and lacking behaviour guidance) is thus simplified to a prognosis. With relation to time, warnings happen before a disruptive event occurs, alerts right after an event (Clausen and Dombrowsky, 1984).

4.1.2 Communicating Weather Information and Uncertainty

Weather information is always afflicted by uncertainty about, for example, the temporal and spatial occurrence of the potential event. The uncertainty arises from a lack of knowledge and incomplete observations, called epistemic uncertainty, and from the inherent stochastic variability and randomness in known and observable phenomena, called aleatory uncertainty (Kox et al., 2015; NRC, 2006). Forecasting uncertainty quantifies intrinsic limits to deterministic (e.g. yes or no) weather forecasts. Improvements in science and technology (e.g. computer models) have made it easier to calculate possible outcomes of the future. A prominent example is the introduction of NWP and the use of EPS over the last decades (Hirschberg et al., 2011; Wernli, 2012). These EPS are one way to make estimates about the uncertainty of weather forecasts, by capturing, e.g. the uncertainty of current initial atmospheric conditions to provide quantitative probability forecasts (Demeritt et al., 2013; Wernli, 2012). This development has partly led to an improvement in the spatial and temporal accuracy of weather forecasts (Hirschberg et al., 2011).

The EPS have a huge impact on the forecast of large-scale and long-lived severe weather phenomena such as hurricanes and winter storms, because the model output sometimes can provide evidence a few days in advance. However, for small-scale and short-lived severe weather phenomena such as thunderstorms, hailstorms, flash floods and tornadoes, EPS currently do not have a larger impact on whether weather warnings are issued by a forecaster or not. In recent years EPS have been used on small scales to delineate, i.e. areas of potential of severe thunderstorms. Mostly, forecasters issue warnings right when an event starts to be measured, or when radar or other data give indications. Such a warning paradigm is called “warn–on–detection” or “warn–on–observation” (Stensrud et al., 2009, 2013). Therefore, the actual forecast lead time (the length of time between a warning being issued and an event occurring) is in most cases short. EPS forecasts are currently only used to state whether the atmospheric conditions make the occurrence of thunderstorms more likely or not. But in recent years, a warning paradigm shift from warn–on–detection toward warn–on–forecast has been postulated (Stensrud et al., 2013). Particular benefits are seen in the improvements of forecast lead times (National Oceanic and Atmospheric Administration, 2015; Stensrud et al., 2013).

However, any *"innovations in forecasting technologies are useless unless they are effectively communicated, understood, and acted upon"* (Demeritt et al., 2013, p. 147) since impacts can be highly dependent on the warning process and the action taken by the receiver (Drabek, 1999; Mileti, 1995). Uncertainty in the context of the communication of warnings mainly relates to epistemic concerns, miscommunication and misunderstanding of the situation. This is due to the fact that risk assessments (and assessors) use concepts with often probabilistic outputs, which are difficult to understand, even for sophisticated decision-makers (Cornell and Jackson, 2013; Kox et al., 2015). Good training in communication and use of such products is important, but fundamental political and institutional challenges in using such information might also exist (Demeritt et al., 2010).

We assume that such a transition to warn–on–forecast would not only change the role of the forecaster (Stuart et al., 2006), but will also affect the practices of forecast end-users and responders to a warning. It is not yet clear how the public or the emergency services would respond to a much longer lead time, whether they can make use of it and whether it would reduce fatalities, injuries and damage (Hoekstra et al., 2011; Simmons and Sutter, 2008). Thus, a fuller understanding of the behaviour of key organizations such as emergency management agencies in creating, using and communicating severe weather information or warnings is needed (NRC, 2006; Stewart et al., 2004). For this we have to look into the actual practices that are or will be carried out during the warning process (Créton-Cazanave and Lutoff, 2013). The question is *"how to deal with risk and uncertainty (in assessment and making decisions) as well as how to organise communication and enhance the integration and acceptance of measures"* (Neisser, 2014,

p. 91).

4.1.3 Research Questions

Following this discussion, we ask whether and how emergency services can make use of recent improvements in technologies and of a postulated shift from "warn–on–detection" to "warn–on–forecast". We take the shift from communicating a deterministic forecast to communicating probabilistic weather information into account and assume that providing uncertainty information allows users to think about the upcoming situation and take decisions at an earlier stage of time under the constraints of given uncertainties. Is there a paradigm shift from "(re)act–on–observation" to "act–on–forecast" or in other terms a *"redefinition of [. . .] practice from alerts to prediction"* (Bruzzone, 2015, p. 179) on the ground? The aim of this article is to investigate this topic by analysing the use of (weather) information by and the present logic of anticipation of the emergency services in Germany and to discuss the findings in relation to the question of how this services deal with forecast uncertainty and weather risks.

To address these questions, we need to know the current emergency services' practice of dealing with severe weather situations and weather warnings in the sense of anticipating future events. We are mostly interested in learning how emergency managers integrate the weather information or warning (and its imbedded uncertainty) into decision-making.

n the following section, we will first introduce the research design and method used for this study (Section 4.2). Section 4.3 focuses on how weather forecasts and warnings are disseminated to emergency managers by the German national weather service (DWD) and what actions are taken by the emergency services to anticipate and respond to severe weather with an emphasis on situation assessments. We discuss the measures taken and the relevance of various information sources like official weather warnings in decision-making (Section 4.4) and draw conclusions (Section 4.5).

4.2 Research Design and Method

This article draws from a set of semi-structured interviews that were conducted with 27 members of the civil protection authorities and administrations from the German States of Berlin, Brandenburg, and North–Rhine–Westphalia, as well as from the DWD. The sample reflects the institutional diversity of German severe weather forecasting, civil protection, and emergency management. Participants were selected based on their specific work tasks to reveal new information on the research topic and to help to make sense of their work experience (Flick, 2012; Froschauer and Lueger, 2009; Longhurst, 2009). The following professionals were of special interest: persons who produce and/or issue forecasts and warnings or are responsible for the development and implementation of warning tools (i.e. forecasters, meteorologists working at DWD); persons who are responsible for the strategic orientation of civil protection (i.e. chiefs of fire departments, representatives of supervisory authorities, associations/unions); and persons who are responsible for the operational deployment of civil protection and emergency management (i.e. emergency managers at command and dispatch centres). This selection led to three groups of potential interviewees. First, firefighters and emergency managers from both city and county levels, who have knowledge about measures and organizational routines based on their own participation and direct observation of organizational practices. Second, members of state or federal authorities who have expertise on organizational contexts based on indirect (or second order) observations (Froschauer and Lueger, 2009) of organizational practices. Third, members of unions and associations and the DWD and the DWD who have an external and indirect perspective on organizational routines.[23]

The data were collected between 2012 and 2016 as part of the interdisciplinary research project WEXICOM at Freie Universität Berlin, carried out in the HErZ (Simmer et al., 2016). Following common qualitative procedures, interviews were conducted and analyzed in an iterative way in order to react to new developments during the interviews

[23]Please note that all interviewees had experience with several disruptive weather events. Germany regularly experiences severe thunderstorms nationwide during the summer season with local hailstorms and occasional urban flooding. Severe winter storm events are also common and occur regionally.

(Flick, 2012). The interviews followed a semi-structured guideline (Witzel, 2000), with a focus on key topics of interest like strategies and measures of dealing with routine and severe weather situations, weather communication tools and content, dealing with uncertainty in weather forecasts, decision thresholds and lead times. All interviewees were informed about the general aim of the research and the funding agency at the beginning of the conversation. Given the sensitivities involved in civil protection and emergency management, confidentiality was important to ensure that interviewees felt safe enough to speak frankly about their experiences (Longhurst, 2009). Quotes and paraphrases[24] are therefore anonymised and contain only the profession and, if necessary, the locality.

A qualitative content analysis approach (Mayring, 2015) was applied in an iterative and inductive-deductive process (Schreier, 2013) to develop a system of categories and corresponding text segments that appeared to be relevant for further examination. The analysis was performed with the support of MaxQDA software, a program designed for computer-assisted qualitative and mixed methods data, by the first author and co-coded in consensual coding (Kuckartz, 2014) together with the second author. In total, 85 codes and sub-codes with an amount of 2341 codings were assigned.[25]

4.3 Responding to and Anticipation of Severe Weather by Emergency Services

To make an informed decision on allocating human and material resources, emergency managers need information about future developments of both the weather situation and its potential impacts.

[24] All interviews were conducted, transcribed and coded in German. Paraphrases and codes were finally translated into English by the authors. Interviewee citations are documented as such. For the original German translation see Appendix E.

[25] For coding scheme, see Appendix F

4.3.1 Dissemination of Weather Information in Germany

Although several private weather companies also provide weather information to the public and special user groups, the DWD is the only agency to issue official warnings by law.[26] The DWD's regional offices, each covering one or more of the 16 German States, are responsible for producing weather forecasts and issuing warnings for their respective region during daytime (see Fig. 4.1. The DWD functions as the official source of information and should give advice, but it is not responsible for deploying any action based on this information.

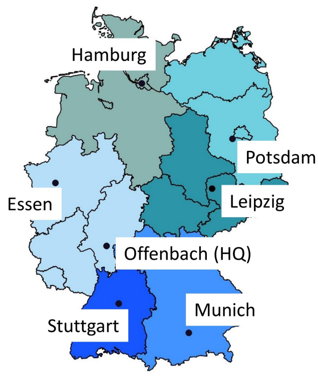

Figure 4.1: Schematic Map of the DWD's Regional Offices in Germany; compiled and designed by the author

Official weather warnings in Germany are organized in a three-step process (see Tab. 4.1 following an increasing sophistication of temporal and spatial resolution: First, early warning information (*"Frühwarninformation"*) on expected severe large-scale weather phenomena, based on numerical models is implemented by the DWD into a 7-day assessment on the intensity and probability of medium-term weather hazards. Second, a 'weather watch' (*"Vorwarninformation"*) is issued up to 48 to 12 hours before an expected regional event. These forecasts are provided five times a day with different reports (*"Warnlageberichte"*) for the whole country, as well as for different regions, to provide users with an overview of the development of the situation (intensification, weakening)

[26]The respective law "Gesetz über den Deutschen Wetterdienst" ("law on the German weather service") is currently undergoing a revision.

within the next 24 hours, including observation data of present events. Besides the regional report a specific ‘severe weather watch’ (*“Vorabinformation Unwetter”*) is issued, which should either be followed by a warning or be revoked. Third and ultimately, official (severe) weather warnings (*“(Un-)Wetterwarnungen”*), follow a colour code (intensification from yellow, ochre, red and purple) and are issued at the municipality level (at the county level until 2016). The lead times depend on the kind of weather event with a maximum of 12 hours. Severe weather warnings are issued for heavy continuous rain, hurricane gale force winds, heavy snowfall, heat, black ice, thaw periods, and thunderstorms. During severe weather situations, updates on the development of the situation are compulsory. No probabilistic information is communicated in terms of numbers. Verbal descriptors are used instead.

Table 4.1: Official Weather Warning Steps in Germany

Lead Time	> 48 h	12—48 h	0—2 h
Warning	Early Warning Information	Weather Watch	(Severe) Weather Warnings
Product	7-Day Assessment	Reports	Official (severe) Weather Warnings
Area	Germany	States	Municipality

DWD forecasters communicate weather warnings to the users as textual information via e-mail and fax, and with additional visual information via the DWD website and a mobile-phone app (*“WarnWetter”*). Fax is widely regarded as the most secure transmission by the interviewed DWD forecasters and managers because this method allows an acknowledgment of receipt. Because the question remains whether the recipient has noticed the warning regardless of the used tool, it might be appropriate to check via phone whether an urgent warning has been noticed.

Some special government agencies such as flood forecasting offices receive raw meteorological data and model outputs they can include as input into their own hydrological models. Other user groups such as road maintenance services and emergency services have access to special DWD online portals, such as FeWIS, fire brigade weather information system) that provide information tailored to their specific region, including up-to-date observational data, satellite and radar imagery, “nowcasting” tools for tracking thunderstorm cells and their movement (*“KONRAD”*, a software for the automatic detection, tracking, and prediction of storm cells based on weather radar data), and the official textual warning with visual and sound notification.

The warning recipient within an emergency service organization may vary due to organizational structures and responsibilities within the organizations. Within a fire brigade control and dispatch center, for example, the commanding firefighter (*"Lagedienst"*) who is responsible for overseeing the coordination and deployment of vehicles and personnel, usually receives the warning.

In the conducted study we asked several commanding firefighters about their experiences in handling warnings and weather reports. Surprisingly, they reported that rather traditional ways of communication, like using the telephone services operated by the DWD regional offices, are an essential communication tool. The phone calls serve as an addition to the automatically distributed weather warnings without any direct user contact and provide the possibility of an oral consultation on present and developing weather situations. The DWD ensures that all incoming calls from emergency services have priority status compared to other calls.

Emergency managers in the control and dispatch centers report that they have nonoperational and more organizational duties, and have a gateway role to process and forward the weather warnings. Thus, they serve as information hubs for other authorities:

> *"We are 'information brokers'. We pick up [information] and pass it on."*
> (Commanding fire fighter, control and dispatch centre, county)

The forwarding of weather-related information usually follows established formal or informal distribution channels to either subordinated or affiliated organizations. The interview partners named several prime examples: weather-related information is forwarded to voluntary fire brigades to be on the alert and prepare themselves for action; to departments of sport and recreation to inform outdoor public sports grounds; to departments of parks to organize pruning work; and to building authorities and public order offices as licensing authorities for outdoor events and venue operators. The information recipients are in most cases decision makers within agencies, but sometimes just receptionists, janitors, or facility managers of governmental buildings who maintain mailing lists for further dissemination. In most cases, the forwarded information does not include weather watches, but is instead limited to the higher threat levels, the official severe weather warnings with the color code red or purple.

> *"We also receive weather watches [...]. However, we cannot jump into action with every notice. Only when we have concrete warnings giving us a concrete indication: OK, something is happening sometime soon..."* (Commanding fire fighter, control and dispatch centre, county)

Forwarding information to local fire stations, subordinate departments, and other governmental agencies aims strongly at inspecting and securing buildings, vehicles, and other assets, for the main purpose of occupational safety or self-protection to avoid any workflow disruption and ensure readiness to act if the weather should affect an agency itself.

4.3.2 Warning Response

Warning responses and related decisions on whether to take any protective measures depend on a number of different criteria. In general, the warning response is influenced by the message, the contextual event, and the receiver characteristics (Drabek, 1999). Decisions are not singular moments (Hacker and Weth, 2012), they must rather be understood as a process of *"differentiated, affectively registered, transformative, and ongoing actualisation of potential"* (McCormack and Schwanen, 2011, p. 2801). Decision-making, may therefore also work through deferral and denial (Adey and Anderson, 2011).

Message characteristics usually refer to the content (hazard, location, time, guidance, and source) and format of the warning message as described above. Event characteristics refer to the hazard's frequency, its magnitude or (physical) impact, speed of occurrence, length of potential warning lead time, event duration, spatial extent or sphere of action, damage potential, predictability, and controllability (Alexander, 1999; Burton et al., 1993; Dikau and Weichselgartner, 2005). The interviews revealed that commanding firefighters must transfer every single information aspect about an event into an overall context of action to take decisions:

> *"The decisive factor is the damage, not the strength of the storm."* (Commanding fire fighter, city)

Such contextual characteristics refer to intervening factors like local topography, demography, building structure, vegetation, and traffic situation, and differ from the characteristics of the event itself. They may vary temporally and spatially, for example, due to the traffic situation during rush hours or seasonal plant cover. In addition, the equipment and characteristics of emergency services may vary considerably, depending on, for example, the size of the work force, the size of the area of operation, and the available (financial and material) resources. Interviewees from state authorities and county fire departments uniformly reported that demographical change in rural areas, for example, causes problems in their volunteer emergency workforces during the week, as people tend to commute to the city for their regular jobs.

Besides individual risk perception and willingness to act, which are influenced by various factors such as sociodemographics, experience, and cultural background (Kox and Thieken, 2017; Mileti and Sorensen, 1990), organizational factors affect warning response. They include uncertainty about the (time and place of the) impact and a tendency to wait until a threat materializes; an informational overload during severe events; and a lack of attention due to a high false alarm rate, or an underestimation of risks (George and Holl, 1997; Meyer et al., 2010). Limited warning response in cases of a high false alarm rate seems to be more a problem of expectation than of reality. As some research suggests (e.g. Dow and Cutter, 1998; Mileti and Sorensen, 1990) this does not hold in real life situations as most warning response will follow once the threat is accepted as such. Confronted with the handling of false alarms (due to forecast uncertainty), emergency managers did state their discomfort but indicated that they would respond to the warning. From the interview data, it still seems to be a major concern for commanding firefighters and other emergency managers regarding the warning response of their subordinates or voluntary units.

> *"You can call-in the volunteer fire brigades at any time. Of course, you must do that with a certain delicate touch – you may have also realized that on Thursday they were not so happy because they were not called into action."* (Commanding fire fighter, control and dispatch centre, city)

The firefighters acknowledge the inherent uncertainty of weather forecasts. Emergency services are by profession trained to regard every warning with awareness because they consistently deal with potentially life-threatening situations. Some of them compare a weather warning to a fire detection system. It is common practice that firefighters always respond to the alarm of a fire detection system with the necessary power of force (vehicles, personnel, equipment) as if there is a fire, although in many cases detection systems give false alarms.

> *"... you have to take every [warning] message seriously. When a fire detection system is activated, it is generally assumed that there is a fire and we will trigger an alarm immediately. Even if the system triggered false alarms three times on the same day [...]. You have to deal with weather reports quite similarly, you do not know what is happening, you must always take [the consequences] into consideration."* (Commanding fire fighter, control and dispatch centre, city)

The consequences of not responding to an alarm or responding with less commitment and thus fewer vehicles, less personnel, and less equipment, would be too costly. It could ultimately result in the fire spreading, leaving many people injured or possibly dead. Therefore, in such cases of life and death, even a high degree of uncertainty about the event taking place would be sufficient to take action. This attitude is comparable to the treatment of weather warnings and, in exceptional cases, may lead to a very preemptive approach to forecast uncertainty as some commanding firefighters reported:

> *"If I get a [warning] message, I start the full program. Then I am also on the safe side."* (Commanding fire fighter, control and dispatch centre, city)

4.3.3 Measures Taken by Emergency Management

Emergency management in Germany follows the principles of federalism and subsidiarity and is organized at the county level (see Fig. 4.2. Counties and major cities are responsible for everyday and less severe events like local fires, small accidents, and regular ambulance services. In weather-related situations, preparatory actions taken by emergency management prior to a disruptive event will typically include closing windows, inspecting roofs, scaffolds, and culverts, and tying up loose objects on the premises, mainly for self-protection and to avoid any surprises or disruptions of the workflow. All this applies only to public spaces and buildings. At this level of severity, private actors, for example local outdoor venue operators, are responsible for making their own decisions on which actions to take.

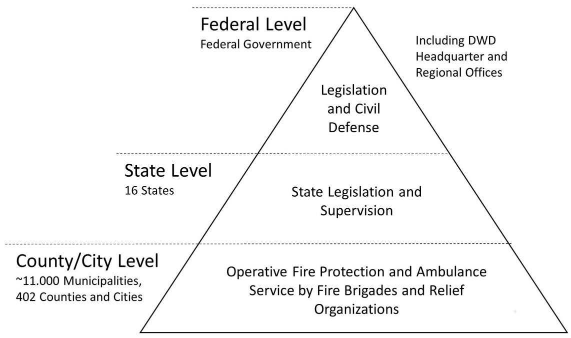

Figure 4.2: Schematic Illustration of Civil Protection and Emergency Management in Germany; compiled and designed by the author based on Geier (2017)

During a weather event, measures predominantly aim at coping with the disruptions caused, that is, securing damaged buildings and infrastructure, pumping water from cellars, (un)blocking access to streets and public places, and so on. Most of these actions are reactive, meaning that the firefighter units receive alerts from their control and dispatch center to respond to the damage because warnings can only lead to preparative measures in the sense of preparing for action:

> *"You can only prepare. Trees cannot be sawn off beforehand for safety reasons. That does not work. And I can only pump water away when it has flooded."*

(Commanding fire fighter, control and dispatch centre, county)

Preparing means that fire brigade control and dispatch centers have the duty to notify their units during an event. Once a center receives an emergency call, it must decide which units from which area will be alerted and sent to scenes of action. To not reach the units' limits[27], measures are generally only taken immediately if the alerts imply a threat to life and property.

> *"What is important are the things, which [...] represent an imminent threat or disturb infrastructures. Such things must be removed immediately. A tree on a forest path can also be left there for three days. That will not bother anyone much."* (Commanding fire fighter, control and dispatch centre, county)

The commanding firefighter has the duty to oversee the situation within his or her area of responsibility, usually a city or county to ensure and maintain the ability to act. If necessary, that means prioritizing missions (the right balance of the best mitigation with the available resources), reallocating staff, vehicles, and technical equipment, and calling-up off-duty units or extending the length of service. In severe weather situations and with an increasing number of missions,[28], interviewees reported that it might also be necessary to adjust operational procedures to ensure the statutory response time. Typical adjustments to the alarm and response regulations include prioritizing specific alarm keywords, bundling missions by location, reducing the obligatory number of vehicles to deploy, and adjusting the obligatory number of people on a vehicle.

> *"...if we do not have the necessary means in that situation, then, obviously, we cannot address the missions in time. That's the consequence."* (Commanding fire fighter, control and dispatch centre, city)

While some commanding officers reported that they would begin to call in off-duty staff at the ochre warning level, others would only begin at a red or purple level. This

[27] For example, not being able to make the statutory response time between receiving an emergency call or alert and arriving on the scene.

[28] This does not indicate a declaration of a state of emergency.

type of pre-alarm is both a physical stand-by and a mental preparation and usually takes less than 1 h. The so-called "cold situation" (commanding fire fighter, control and dispatch centre) involves non-personnel preparatory measures concerning vehicles and equipment (for example, submersible pumps or chainsaws) and personnel preparatory measures like calling in additional dispatchers to the command center, reallocating staff within the jurisdiction, or activating special units like wild fire units. Some fire brigades report that they make use of "scouts" (*"Erkunder"*), usually one person (with emergency management qualification) in a small vehicle. That person takes a closer look at the reported disruption and decides whether (and with what priority) or not any actions should be taken if the information provided by the emergency call remains uncertain. Not all fire brigades take such stand-by measures, and they are more common in cities than in rural areas. During an event it might be necessary to issue a second alarm, which means extending personnel's length of service, reallocating personnel, or calling in off-duty units and volunteer firefighters.

Some of the measures are formalized in operational plans and special guidelines for actions during severe weather situations.[29] These plans specify the measures for different alert levels based on an event's magnitude (wind speed, water level) or the extent of impact (number of casualties, number of deployed personnel). However, not all departments have such plans prepared and available, and some organizations have developed their own, often unformulated, procedures based on experience. A typical example of a general guideline is the *"Feuerwehr Dienstvorschrift 100 (FwD100)"*, a regulation or manual best compared with the US Incident Command System (Bigley and Roberts, 2001). The FwD100 provides guidance for management, coordination and control of mass-casualty incidents and other emergencies. Such plans regulate how information is processed, what actions are taken, and who is responsible. Like Bigley and Roberts (2001) show for the US Incident Command System, the FwD100 is not a rigid framework. It is rather adaptive, very loosely worded, providing room for interpretation and allowing

[29] One example is the 2002 guideline *"'Umgang mit Wetterwarnungen"* ("dealing with weather warnings") of the German fire fighter association vfdb.

flexibility (Ellebrecht and Jenki, 2014).

4.3.4 Situation Assessment: Collecting Weather and Impact Information

The interviewees reported different sources for situation assessment. In addition to weather warnings, news broadcasts, personal contacts, and emergency calls provide relevant information for situation assessment. The interviewed commanding firefighters emphasized that a comprehensive situation assessment is of paramount importance for preparing their response:

> *"The fire brigade's response does not depend on the warning, but on the assessment [of the situation]."* (Commanding fire fighter, state)

The term "situation" usually refers to the period shortly after or during an event when the responders have to deal with the impact. The assessment, therefore, includes all available information about the current and future weather development, as well as the current impact, that is, the damage and disruptions caused. If early signs of a potential disruptive event are visible beforehand, it is desirable that the assessment should start at an earlier point in time.

> *"We always try to get a bit ahead of the situation by collecting information, evaluating different networks, to have information early on, preferably before an event..."* (Commanding fire fighter, control and dispatch centre, county)

In addition to the DWD information described above, the responsible officers in the control and dispatch centers use weather reports on TV, radio, or Internet. If the weather situation is uncertain, or the initial information or warning text is unclear, some emergency managers stated that they contact the weather service's regional office for further advice. The consulting service offered by the meteorologists from the regional offices is a low-threshold service as described above and the additional information often serves as a decision template.

> *"... having an expert explain it properly once again. Is it as I think it is, or will it develop a bit differently? It is more about getting confirmation. We all surely are no [weather] professionals."* (Commanding fire fighter, control and dispatch centre, county)

Some interviewees reported that they prefer to consult their "own sources". This includes units on patrol, who are potentially more exposed to the weather, or local ambulance helicopter crews, who get specific flight weather data that contains more detailed information. In addition, some interviewees indicated that their own exposure to the weather, either during work shifts or during their leisure time, contributes in some way to the assessment and verifies the current weather situations by simply "looking out of the window" (state police officer) or "feeling the mugginess" (commanding fire fighter).

During an event, situation assessment builds on additional information about impacts. In the case of a major event, media coverage will soon start after the first disruptions become visible. The commanding firefighters reported that they begin to pay more attention to the news to gain information about what is going on outside. Additionally, they may contact other fire stations further upstream of a storm track that might already be affected by the event and mirror the impending impacts to their own region by extrapolating the (thunder-) storm (cell) track on the precipitation radar or KONRAD.

> *"And if something is approaching from the west, it would be interesting to know how it looks right now in [name of city]. And if we learn from the control centre that they are being deluged, the chance is relatively high that it will also happens to us. That would be reliable information."* (Commanding fire fighter, control and dispatch centre, city)

Local impact information is based mainly on mission reports and emergency calls. Usually, (written) mission reports provide ex post facto information about an event, its impacts, and an analysis of the coping measures. They fulfill the purpose of post-processing and training. Conversely, ad hoc reports, based on local situation assessment and feedback from local officers-in-charge, can provide ground truth about the impact during an event. "Scout" reports, although not considered as missions per se, fulfill the same objective. In addition, most control and dispatch centers have information technology that provides them with information about the occupancy of their vehicles. Such information is primarily used to adjust measures if not enough capacities are on hand to respond within the statutory response time. However, occupancy information is also a good indicator of impact.

Similarly, emergency calls have two different features: They are both a source of information about the impacts, and, because of the event, a disruptive impact (of the daily routine) for the emergency services themselves. The number of emergency calls varies in space and time. The interviewees reported that there are regional differences (for example, city-rural) in when and how often people make an emergency call, and temporal differences between day and night. Especially damages to property, like loose roof tiles or flooded cellars, are often not recognized after dusk and reported only in the morning. Another peak in calls occurs in the late afternoon when people come home from work.

4.4 Discussion

As shown, apart from the coordination and deployment of missions as a response to an event, most measures taken prior to or during emergencies aim to achieve and maintain an organization's ability to act. While long- and mediumterm warnings and weather watches enable emergency organizations to prepare for responding to a potential event, short-term warnings, nowcasting, and regularly updated observational data of the ongoing event enables an organization to act accordingly during an event. Providing information on meteorological uncertainty, such as the probability of rain or the probability of exceeding a certain threshold such as a warning level, makes it possible to deviate from the temporal restrictions of official warnings and to provide information on possible events already in the temporal domain of a weather watch. This allows forecasters *"to derive products tailored to specific customers"* (Stuart et al., 2006, p. 2). The desired benefit is that this enables end-users of forecast information to start sooner with preparatory protective action based on the enduser's own risk assessment and decision threshold.

However, those developments in meteorology and weather forecasting do not necessarily fit the current practices of the emergency services, that is, rescue and firefighting, as the presented results show. These practices are still mostly carried out based on alarms and ground truth in a superficial reactive manner, rather than through anticipation based on prognosis or forecasts. This is mainly because the specific characteristics of the basic tasks of rescue and firefighting are not predictable per se. Or as Apelt (2014) pointed out, it is unpredictable at what intervals a fire must be extinguished and people must be saved. Demeritt et al. (2013, p. 154) raised more institutional concerns when they linked *"legalistic traditions of expert management"* with the *"tendency to wait for confirmation before acting on medium-term alerts from EPS."* Nonetheless, in the data there are several examples of anticipatory action, including preparatory measures of personnel planning and deployment of equipment. Other measures show signs of a both proactive and reactive character that is preparedness and response. Actions like pre-alarm and adjustments to operational procedures are preparatory – they enable the preparedness to respond. At the same time these actions are reactive, because they are only taken as a response to a manifested event, when a level of tolerance is exceeded (that is, the number of emergency calls, deployments, or missions), or as a response to first indications for an event, more exactly a particular probability of occurrence or a warning level.

That does not mean that emergency services take measures only if the impacts reach a certain threshold of tolerance. In contrast, it seems that most kinds of actions take place almost all the time during the development of an event as they compare their different information sources. Severe weather events are a common hazard and there is a consciousness and knowledge about what might happen as the potential impact of such an event. In general, reactive behavior seems to be due to the self-understanding of the organization since it has to be lightly 'proactive' when it is permanently on stand-by, ready for an alarm and ready to act. Likewise, Demeritt et al. (2013, p. 154) argued in the context of European flood forecasting that one reason *"agencies have sometimes set quite high confidence thresholds for issuing flood warnings is that their statutory responsibility is public safety."* Thus, they focus on shortterm warnings to support response measures such as public evacuations, rather than on medium-term forecasting in supporting mitigation (Demeritt et al., 2013). It seems that in this context, the weather warning only serves as confirmation of what is already planned and decided on.

As outlined in the introduction, weather information always includes uncertainty, including about the expected place and time of occurrence, the intensity of an event, the extent of impacts, and the warning response. In addition, there is uncertainty concerning issues of misunderstanding and misinterpretation of the warning message content.

The interviews reveal two different approaches to dealing with uncertainty. First, there is a recognition of hazards and uncertainties, which results in a temporizing or observant and rather reactive behavior, and adaptive coping measures. Such adaptive behavior aims mostly at the preservation of the organization's function to ensure the preparedness to respond and the organization's ability to act in a timely manner. This aim is also reflected in the significance of occupational safety for decision making and the choice of measures. Emergency services will always protect themselves first to be able to help others. This behavior is typically found in routine and often trained situations. When receiving a warning, commanding firefighters, police officers, and other emergency managers cope with uncertainty by collecting, comparing, and blending different information about the uncertain event and its uncertain outcomes within the situation assessment to validate the information.[30] However, even if misinterpretations of weather forecasts are revised, uncertainty about the potential outcome and thus the controllability of response measures always remains. To combat this uncertainty, emergency managers stated that they consult different sources in addition to the DWD meteorologists. Some commanding firefighters consult colleagues upstream of a storm track to gain ground-truth evidence of impacts that have occurred there and try to extrapolate this to their own region to anticipate potential impacts. These findings are in line with other studies on collabora-

[30] As shown, decision makers may as well base their weather-related decision making on private life situations, as non-extreme weather events are daily experiences, and the confidence in the weather forecast is often proven and can be self-verified moments later. However, even emergency managers, especially in most parts of Europe, are seldom exposed to very extreme weather events like tornados (Doswell, 2003).

tive crosschecking and confirmation-seeking in emergency management (e.g. Baumgart et al., 2006; Demeritt et al., 2013).

The second approach can be described as a 'zero-risk strategy', in which even the lowest probability of occurrence is too much of a risk and thus has to be avoided. This is mainly due to the nature of most of the potential hazards emergency services have to deal with: They can always lead to deaths. Another reasonable explanation is the selfunderstanding of the organizations as ensuring public safety and responding adequately to any given risks. Therefore, such preemptive behavior can be found especially with regard to high-magnitude, low-frequency events with known but potentially catastrophic consequences, such as fire. The usual way of responding to the automatic alarm of a fire detection system in a school building or a tower block is a typical example that was repeatedly noted by the interview partners. In these situations, *"when failure isn't an option"* (Hillmann et al., 2005), not acting on a warning is seen as a risk not worth taking. Even if it is recognized that – despite all measures – the attempt to generate maximal safety is an illusion, the principle "better safe than sorry" prevails. Or in the words of Adey and Anderson (2011, p. 2884): *"Within the logic of preparedness, harm may be a consequence of something done or not done in response."*

While measures of preparedness are based on warnings, most actions occur as a response to or during an event and are mainly based on observational weather data and ground truth. This includes measurements like wind speed or the amount of precipitation, impact reports from neighboring communities, fire brigades and media broadcasts, traffic reports or by noting the increased operational pressure and thus personnel expenditures due to an increase in emergency calls and missions. In these cases, the problem is not the weather event itself, but rather that other non-weatherrelated missions (responding to a heart attack, stroke, and so on) have to stand in line and face possible delay. Due to the additional expenditures, the weather event makes it even harder to fulfill these core duties. It seems that the characteristics of the specific weather phenomena, that is, whether the precipitation results from a large-scale event or from a small-scale convective event, do not play a key role from the emergency-management perspective.

The decisions and measures rather depend on the impact, not on the precipitation itself, but on flooded basements, overflowed streets and overflowing sewer systems that cause the disruption to the organizational routines.

4.5 Conclusion

These findings support the need for impact-based warnings. Concentrating on the importance of communicating weather impacts rather than characteristics of events alone points away from a process-oriented toward an impactoriented situation assessment. Additionally, a shift from deterministic to probabilistic weather warnings would emphasize preparedness in risk management. This would mean accepting uncertainty and dealing with weather hazards in an adaptive manner. The so-called warn-onforecast paradigm is one explicit example for anticipating the future around disruptive severe weather events. Such a transition in warning behavior of national weather services would also imply a paradigm change concerning the current practice of response to weather warnings for most emergency organizations. Only then could emergency managers benefit from longer lead times.

5 Synthesis and Conclusion

In this chapter the main achievements of this thesis are evaluated with respect to the overarching research questions introduced in Section 1.2:

a) which factors influence the decision-making with respect to the perception of uncertainty in weather forecast; and
b) how do forecast users make use of probabilistic information and the additional lead time and how is the weather forecast (or warning) reflected in their decision-making?

The chapter is structured into two sections – perception of uncertainty in weather forecasts and use of uncertainty in warning response – summarising the contributions of the single studies along the two overarching research questions, and a final section that provides concluding remarks and an outlook for further research.

5.1 Perception of Uncertainty in Weather Forecasts

Uncertainty is an essential part of atmospheric processes and, therefore, "*no forecast is complete without a description of its uncertainty*" (NRC, 2006, p. 98). The results of all three studies shows that the uncertainty in weather forecasts is experienced by and is visible to forecast recipients in many different ways. Not only the general public (see Kox and Thieken (2017) in Chapter 3), but also more sophisticated user groups like the emergency management community (see Kox et al. (2015) in Chapter 2, and Kox et al. (2018) in Chapter 4) are very heterogeneous. As revealed by the studies, they differ with regard to their perceptions of risk and uncertainty, their level of weather-related knowledge and understanding (e.g. meaning of numerical forecasts) and their requirements and needs (e.g. lead times and decision thresholds for preparatory action).

Especially the emergency management community is additionally influenced by different legal and institutional constraints.

The studies presented in Chapter 2 and Chapter 3 showed that people have a sense for uncertainty in weather forecasts. Due to the daily experience of weather at least people who regularly receive warnings notice that not all of them are correct. Nevertheless, when asked for their confidence in weather forecasts (or belief in the reliability of a weather forecast), they correctly (Balzer, 1994; Murphy and Brown, 1984) judged 2-day forecasts as more accurate (or more skilful) than 7-day forecasts by expressing less confidence in longer lead time forecasts (see Fig. 2.1 and Fig. 2.2).

Furthermore, the study presented in Chapter 3 showed that if confronted with probabilistic information, the decision threshold whether to take action was altered significantly by the event's severity, the consequences, and socialisation, cultural background and values such as individual experience, education, housing status and ability to act. Socio-demographic determinants alone were not sufficient to fully grasp risk perception and protection behaviour (see Fig. 3.2).

The identification of the factors that influence individual decisions to respond to weather information and take protective action might help to reveal the different dimensions of risk perceptions with respect to severe weather events. NHMS and other weather services should recognize that the general public and other forecast users are not a homogeneous group. Weather information will never be perceived in the same way by different audiences. It is therefore recommended to be transparent and open about the uncertainty inherent in weather information and to communicate this information. This would enable users to tailor the forecast according to their own individual or organisational risk tolerances (see Section 5.2).

The communication of weather forecasts in Germany is still predominately issued as deterministic forecasts. Numerical estimates of forecast uncertainty are uncommon, with the notable exception of probability–of–rain forecasts featured on most websites. However, forecast uncertainty is communicated in verbal terms. For instance, DWD's early warning information includes qualitative statements about the forecast uncertainty using verbal statements indicating gradations of the likelihood of occurrence of a weather event (see Section 1.1.3). Additionally, the regional warning reports contain "*a plethora of unspecified uncertainty terms*" such as 'occasionally', 'can occur' or 'are expected' (Pardowitz et al., 2015, pp. 626–629).

The study presented in Chapter 2 clearly illustrates the problem of ambiguity and vagueness (or linguistic uncertainty) associated with the communication and perception of weather forecasts. The results show that numeric associations (0 % to 100 %) to the different verbal expressions of uncertainty (here, the terms *possible*, *likely*, *very likely*, which are used in the DWD's early warning information) scatter greatly. This indicates that all terms are highly under-specific and thus subject to major variability in interpretation. With the exception of the very low probabilities (0 % to 10 %) every term overlaps every other term (see Fig. 2.3), expressing the vagueness of the terminology. As shown, the terms *possible*, *likely* and *very likely* can mean something totally different from one person to another (Pardowitz et al., 2015; Regan et al., 2002). The under-specificity can best be treated by specifying the relationship between words and numbers and by using defined categories (Murphy and Brown, 1983; Pardowitz et al., 2015).

So, even if uncertainty in weather forecasts is accepted and taken for granted by many forecast recipients, the uncertainty about the uncertainty may lead to serious problems in the communication of weather forecasts and warnings. As such problems relate for the most part to epistemological concerns[31], they can be reduced to some degree by obtaining more knowledge, hence, educating the forecast user. While it might be nearly impossible to comprehensively educate the public, other user groups such as the emergency management community might be more relevant as they have to deal with weather events and warnings regularly by profession. Additionally, they receive training on how to handle

[31]Merz and Thieken (2005, p. 117) suggest clearly separating epistemic and aleatory uncertainty in risk and uncertainty analysis "*to make more informed management decisions*" as the "*separation of uncertainty is more informative and gives a more complete representation of the process and the appropriate management response.*" Thus, it is revealed which kind of uncertainty can be reduced by gaining more knowledge (epistemic uncertainty) and which is not reducible (Merz and Thieken, 2005, 2009).

weather information platforms such as DWD's fire brigade information system FeWIS, where meteorologists train fire fighters how to use the platform and how to interpret the forecast. It is therefore recommended to maintain and/or extend the collaboration of the weather services with their key user groups. This also implies that meteorologists and forecasters can learn and understand the user's needs, requirements and communication constrains and adapt their communication strategy accordingly. Such collaborations would also enhance the user's trust into the information source. As the study presented in Chapter 3 showed, the trust in the source of information significantly influences decision-making with respect to probabilistic information towards a less risk-avoiding behaviour (see Fig. 3.4). The establishment of a trust-based collaboration between NHMS and their key users is the basis for the implementation of probability estimates in weather forecast.

5.2 Use of Uncertainty in Warning Response

Using information about uncertainty demands awareness about and acceptance of the limits of knowledge (Brown, 2010, p. 76), hence, a) the capabilities of the forecaster to anticipate future developments through practices of calculation (Anderson, 2010), and b) the capabilities of the user to make sense of this information, in particular to reflect upon an upcoming situation and to make decisions at an earlier stage of time under the constraints of given uncertainties.

5.2.1 Uncertainty in Decision-Making Processes: Preparedness and Prioritisation of Measures

In this context, Brown (2010, p. 75) calls for an more "*open treatment of uncertainty.*" Being open and transparent about the uncertainty in weather forecast means to appreciate social and psychological causes of uncertainty and the imperfection of knowledge and observations. Such an understanding could help to set the focus in decision-making and enhance the proper weighting and prioritisation of measures (Brown, 2004, 2010), beyond the purely deterministic options of either taking immediate action or not taking action. In other words, of rash risk-avoidance or naive fatalism.

While deterministic forecasts demand ad hoc decisions based on the currently available information, periodically updated forecasts (in a nowcasting time range) including forecast uncertainty allow the user to step into a negotiation process about whether to take action and to what extent while the potential event develops. The longer the time range, the more the forecasts take the shape of scenarios of alternative futures (see Fig. 5.1) and the type of preparatory measures and their lead time will change.

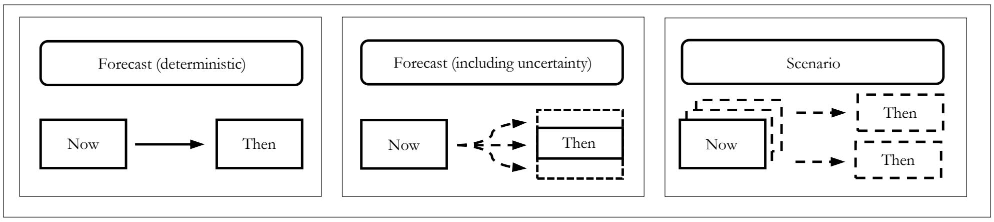

Figure 5.1: Forecasts and Scenarios; compiled and designed by the author

Emergency services might plan their preparedness measures like the call-in of fire fighters or the allocation of resources according to that information. They might accept losses at one locality in order to protect another locality of higher priority. They might decide to send home units that have be on duty for too long in order to have fresh units available on the following day and be able to respond to other dangers such as a major fire or other accidents that could cause bigger problems than the current weather event.[32]

The use of probabilistic information based on EPS model outputs to calculate future developments of the atmosphere is a good way to be transparent about the uncertainty of weather forecasts. It would allow users to take action based on their own risk tolerance. However, the study presented in Chapter 4 showed that probabilistic weather information is rather useless unless it is incorporated into the decision-making processes. Besides an open treatment of uncertainty, this must include the opportunity that the user is able

[32] Please note that such examples show that inevitably a negotiation partner is needed to gain benefit. Additionally, several optional measures have to be available in order to prioritise them. Parts of the general public will not have that option in many of their daily decisions and would therefore not benefit as much as organisational users.

to adapt practices with respect to the upcoming weather situation. Drawing on the example of emergency services, it could be shown that this is not necessarily given, as practices are mostly reactive and carried out on alarms and ground truth rather than based on a forecast.[33] Fig. 5.2 sketches a fictitious decision-making process towards the construction of a '*situation picture*' prior and during weather events in a fire brigade control and dispatch centre based on the findings of Kox et al. (2018). Prior to a weather event, the commanding fire fighter receives weather information via DWD, the media and their own exposure to the weather. Forecast uncertainty is reduced by cross-checking and confirmation-seeking (e.g. Baumgart et al., 2006; Demeritt et al., 2013) like consulting a DWD meteorologist or other sources upstream of a storm track to gain ground-truth evidence of impacts. The study revealed that the local impact of an extreme weather event is mainly apparent for fire fighters in form of emergency calls and subsequent mission or dispatches.

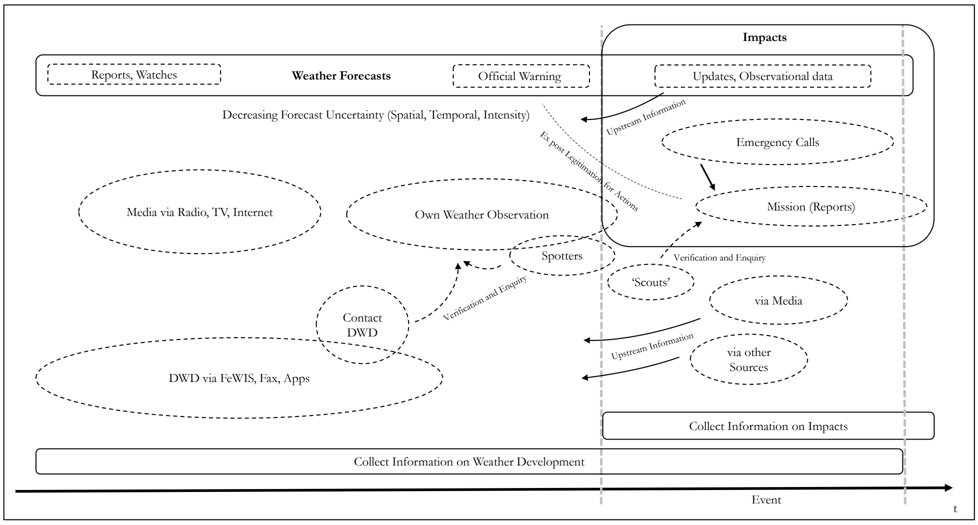

Figure 5.2: Application of Weather Forecasts to Create a Situation Picture; compiled and designed by the author based on Kox et al. (2018)

To sum up, while meteorologists are generally interested in knowing something about uncertainty in their research and are concerned with quantifying and reducing uncertainties, decision-makers are rather concerned with prioritising their actions (i.e. finding the

[33]Despite the lack of evidence, it can be expected that the public will show similar behaviour.

right balance of the best mitigation with the available resources, see Section 4.3.3), and selecting from fixed options, i.e. rather base their decision on a deterministic yes–or–no forecast than on a probability, particularly if they expect to be held accountable (Brown, 2010; Goodchild, 2009). Additionally, weather forecasts must be seen as just one set of knowledge against that the user is entitled to compare and to use their own knowledge and experience (Cornell and Jackson, 2013).

5.2.2 Impact-Based Weather Forecasts

The exploratory study presented in Chapter 2 indicated that participants from the emergency management community tend to avoid forecasts based on low probabilities for their decisions (see Fig. 2.5). It might be that they refer the probability statement not to the likelihood of a weather event but to possible consequences. This finding is in line with previous studies by, e.g. Demeritt (2012) or Joslyn and Savelli (2010), statements from emergency managers presented in Chapter 4, and the results from the study presented in Chapter 3. The latter study showed that besides the severity of a weather event, the value of the property at risk, or in other words the negative consequences of not taking action, influence the public's decision to act (see Fig. 3.1).

All these findings support the call and need for impact-based warnings. This means communicating the expected impact of weather rather than the characteristics of a weather event alone (WMO, 2015). Such a forecast (see Fig. 5.3) may be estimated on the relation between a weather event, local intervening factors such as vulnerability, population density, traffic, building structure, topography or vegetation, combined with information about, e.g. financial losses in insurance data (e.g. Donat et al., 2011) or data on emergency calls or dispatches (e.g. Bassil et al., 2009; Pardowitz, 2017).

As impact-based forecasts would provide information about potential consequences, they could offer information closer to the users' reality and their decision-making compared to a common weather forecast (see Fig. 1.1). It may thus improve the understanding of weather warnings and (appropriate) responses like, e.g. the decision about extending the length of service for voluntary fire fighters or the allocation of vehicles and personnel (see Fig. 5.3).

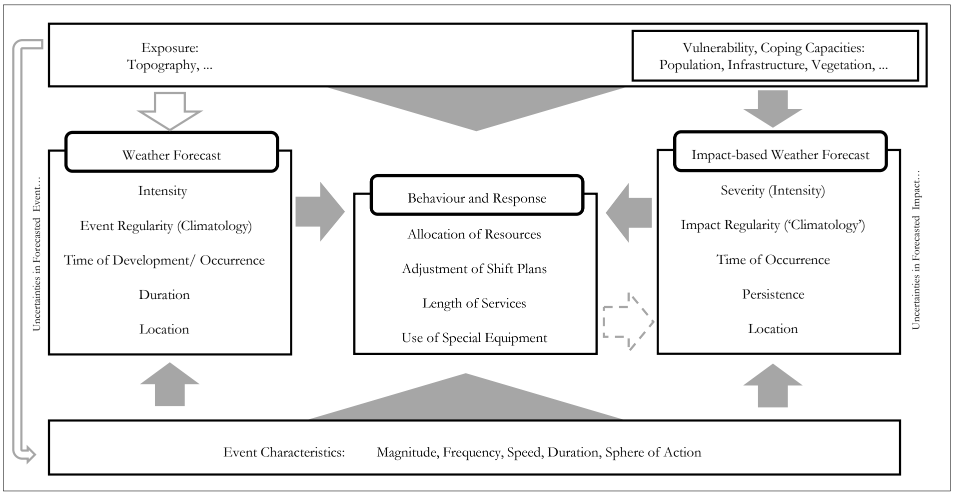

Figure 5.3: Weather Forecast and Impact-Based Weather Forecast; compiled and designed by the author

Combining forecasts on expected impact and NWP can then be used to develop risk-based weather warnings, specifying the likelihood of a hydro-meteorological hazard accompanied by its potential impact. Some laboratory research (e.g. Casteel, 2016) shows the value of risk-based warning approaches. However, real-life data on the use and effectiveness of this warning system are often missing. As one of the first major NHMS, the UK Met Office has recently moved towards risk-based warnings, issuing weather warnings incorporating the expected impact (Neal et al., 2013). A comparable approach does not yet exist in Germany. Yet, such an approach has the potential to support specific user groups in taking effective and efficient measures and leads away from a process-oriented toward an impact-oriented risk assessment. It would also mean accepting uncertainty as inherent characteristic of weather and weather communication and dealing with weather hazards in an adaptive manner.

However, there are still many challenges to face. Firstly, to establish such a forecasting system, the users have to know their risk tolerance, hence, their decision threshold. This might be a difficult task, especially if it concerns the general public. In other cases, like with emergency services, this should be an integrative discussion between the provider of the information and representatives of the user group about the user- and case-specific presentation format, thresholds and communication means prior to an event. Post-event audits (or just a telephone call in the simplest cases) between the commanding fire fighter and the forecaster responsible for that area would strengthen the cooperation and mutual understanding.

Secondly, the consequences of weather are difficult to quantify as they can mean many things to different people. In the case of emergency services it could mean an increase in emergency calls and missions as described above (see Fig. 5.2). More generally, consequences of weather can range from a fallen tree to the disruption of infrastructures to the loss of life; or from financial losses to the loss of reputation or the loss of an image as someone who guarantees public safety. In many cases, the consequences of not responding to a warning or responding with less commitment (i.e. less vehicles, personnel or equipment) would often be too risky. In addition, it is unclear what impact, consequences or severity might mean for each individual or organisation. While a meteorologists measures the severity based on the magnitude and frequency of an event, an emergency manager might see the first snow or the first major storm of the season as more severe than an event of higher magnitude a few weeks later because of the expected public response (see also Spinney and Gruntfest, 2012). Forecasters should be aware of this and formulate their warnings accordingly.

Thirdly, the real impacts may differ from the predicted impacts. With estimates about the potential impact, a further source of uncertainty is added into the forecast. In addition to the uncertainty about the event characteristics, uncertainty about the characteristics of the event's outcome have to be accounted for. A fact that makes it even more important to be open and transparent about the uncertainty.

Fourthly, there will be uncertainty about the (public's and emergency services') response to a warning and about the influence of the warning on this response. Even though the factors that influence protective action may generally be known (see study results in Chapter 3), the actual social composition of the warning recipients during a crisis situation remains blurred. Thus, the uncertainty in the anticipation of warning response is mainly ontological and consists of ignorance about the public's and emergency services' behaviour. It is simply impossible to make valid estimates about the public's behaviour in extreme situations. This unpredictability (ontological uncertainty) has to be accepted as something that will not change in the foreseeable future.

Fifthly, the character of the intervening factors may change over time. The public's transport behaviour and the communication and technology they use may change. Emergency services may adapt their processes and planing towards a specific hazard. In addition, urban development takes place and technical improvements like new rainwater sewers, or modifications in settlement and building structure may come to be. All these changes will have an influence on the impact of a weather event, however, they will not necessary lead back to modifications of the forecast or warning procedure (illustrated by the dashed arrow in Fig. 5.3). Especially in situations where a warning was successful (i.e. if losses could be prevented) it is incomprehensible if the warning actually caused the behavioural change. An example of the 'paradox of prognosis' or 'self-destroying prophecy' (Clausen and Dombrowsky, 1984), the situation that a damage does not occur in the first place due to a effective warning. While this effect is generally desired, it complicates the evaluation and the legitimisation of a warning hindsight.

5.3 Concluding Remarks and Outlook

The perception and use of weather warnings have been addressed in several studies in the past, mainly in the US and UK and with focus on lay people. So far the research on this topic had not been sufficient for Germany or the emergency management community in particular. Over the last years several national and international programs such as the SERA working group, WAS*IS or more recently the WWRP High Impact Weather Project have been at least partly dedicated to the issues of forecast uncertainty communication. They all share the common recommendation that uncertainty has to be recognised as an integral part of weather. It is thus a major issue with respect to the communication of weather in forecasts and warnings.

This thesis provided insights into the perception and use of information of weather forecast uncertainty by the German public and German emergency services. The presented studies show that the general public and emergency services in general accept uncertainty as inherent to weather forecasts, although, this should not be regarded as a preference for probabilistic forecasts as deterministic forecasts are still closer to the user's practices of weather warning response. While the uncertainty in atmospheric processes and in weather forecast is accepted, uncertainty in weather warning is a problem. Generally, the warning recipients expect deterministic advice on how to act appropriately. Drawing on the example of emergency services, it could be revealed that there is a tendency to avoid forecasts indicating low probabilities of occurrence as a basis for decisions. On the one hand, their current practices of warning response is not ready to incorporate probabilistic statements into their decision-making processes. On the other hand, it might be that they connect the probability statement not to the likelihood of an event but to possible consequences. Especially in the case of the emergency community, those consequences are difficult to quantify.

Due to the limits of quantitative methods, it is therefore recommended to apply qualitative methods in further research, i.e. interviews with decision-makers and ethnographic approaches like observations of forecasters and forecast users, to gain knowledge about the practices carried out in the production, dissemination and application of weather warnings.

Whenever trying to enhance weather forecasting, it must be distinguished between the different kinds and sources of uncertainty and their respective meaning for communication. NHMS and private weather companies should not only focus on improving their models and observation tools, but should also work on communication and collaboration aspects of weather forecasting. Even though there are exceptional positive examples, there is still insufficient interaction between forecasters (or meteorologists in general) with their user community. Weather services should also recognise the heterogeneity of their users and discussions should be an integrative and transdisciplinary process involving provider and the user of the information. The emergency management community might be a suitable target group to establish (or enhance existing) collaborations. If impact-based warnings should be implemented, forecasters will rely on impact data, which can be provided through such a cooperation. In this context, forecasters will learn about what is regarded as impact by the warning recipient. The joint confrontation with and discussion about forecast uncertainty might also contribute to a deeper understanding of numerical weather information.

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A Questionnaire Emergency Services

The survey questions discussed in this paper are presented below. Please note that the original questionnaire consisted of 20 different questions in German. This is a translated selection and the question numbers and order do not correspond to the actual questionnaire. The formatting has been altered for space considerations.

Question 1: Which of the following weather phenomena is most relevant for your work? (Multiple answers allowed)

a) Strong wind and gusts, b) Heavy rainfall, c) Thunderstorms, d) Snow, e) Glazed frost, f) Hail, g) Continuous rain, h) Thawing

Question 2: Which mitigation measures are regularly taken into account on the basis of a severe weather warning?

(Open-ended question)

Question 3: Do you or your organisation forward weather information and/or warnings to other organisations, or provide other organisations with weather information? If so, who is addressed?

(Open-ended question)

Question 4: Did you experience any problems when forwarding weather information to other agencies or organisations? Please give examples.

(Open-ended question)

Question 5: Did you experience any problems when receiving weather information from other agencies or organisations? Please give examples.

(Open-ended question)

Question 6: How high is your confidence in the accuracy of a 2-day/ 7-day forecast regarding a) temperature, b) chance of precipitation, c) amount of precipitation, d) chance of thunderstorm or e) chance of storm?

(Scale: very low, low, high and very high.)

Question 7: Medium range weather forecasts (e.g. 7-days) tend to have greater uncertainty than short range weather forecasts (e.g. 1–3-days). In which way do you prefer to receive medium range weather forecasts?

a) Single values (e.g. "the maximum temperature will be 35℃")
b) Range of values (e.g. "the most likely temperature range will be between 32℃ and 36℃")
c) Probabilistic values (e.g. "there is a 85% chance of the temperature exceeding 28℃; a 30% chance of the temperature exceeding 30℃; a 10% chance of the temperature exceeding 36℃")

Question 8: If in the future forecasts will be made on the basis of probability statements, would you still need deterministic information (i.e. detailed information on rainfall or wind speeds etc.) for your work?

(Yes, No)

Question 9: Imagine DWD states the advent of an upcoming storm in your region with the indications "possible"/ "likely"/ "very likely". Which of the following probabilities would you associate to this forecast?

(Scale: 0%–100%; 10% intervals)

Question 10: Which lead time do you need to start with (preliminary) actions? Please indicate the approximate time needed for the most important actions.

(Open-ended question)

Question 11: A storm is forecasted for the next day. On which forecast would you or your agency/organisation start with preliminary measures? Based on a probability of...

(Open-ended question, numerical probability expressions only)

B 'Garden Scenario'

The 'Garden Scenario' discussed in this paper is presented below. Please note that the original questionnaire was in German. The formatting has been altered for space considerations. The scenario was placed half way through the questionnaire and split on two pages.

Imagine you own a garden centre. For a long planned garden show in spring, some plants have been placed outside some days before. Some of the plants are **sensitive to frost**.

A day prior to the garden show you listen to the weather forecast for the coming night. The forecast indicates a probability for frost. **Starting from which level of probability for frost would you take action, if you relied exclusively on this weather forecast?**

1. Scenario

The forecast for the coming night predicts slight frost (temperature below 0℃). Which probability for slight frost would motivate you to place all plants back into the greenhouses for the night?

(a) I'd place all plants back if forecasts indicate a probability of...

(b) I would under no circumstances place back the plants.

2. Scenario

severe frost (temperature below -10℃)

(a) I'd place all plants back if forecasts indicate a probability of...

(b) I would under no circumstances place back the plants.

next page

The Botanic Garden decided to place some additional, **especially valuable plants** outside which are also sensitive to frost.

3. Scenario

***slight frost (temperature below 0℃) ***

(a) I’d place all plants back if forecasts indicate a probability of…

(b) I would under no circumstances place back the plants.

4. Scenario

*** severe frost (temperature below -10℃) ***

(a) I’d place all plants back if forecasts indicate a probability of…

(b) I would under no circumstances place back the plants.

C Questionnaire Public

Please note that this are only the questions discussed in the paper Kox and Thieken (2017) and the order does not correspond to the actual questionnaire. The questions referring to the scenario are part of the Appendix B. The formatting has been altered for space considerations. The original questionnaire was in German. If not stated otherwise, questions have been answered using a 5-point Likert-type scale that ranged from 1 (strongly disagree) to 5 (strongly agree).

Original German questionnaire	English translation
Informieren Sie sich über das Wetter? Wenn ja, welche Quellen nutzen Sie vor allem?	Do you inform yourself about the weather? If yes, which sources do you use?
A: Fernsehen	A: TV
B: Radio	B: Radio
C: Tageszeitungen	C: Newspapers
D: Webseiten	D: Websites
E: Smartphone Wetter-Apps	E: Smartphone weather apps
F: SMS/FAX Benachrichtigungsdienste (inkl. KATWARN)	F: SMS/FAX information service (incl. KATWARN)
G: E-Mail Benachrichtigungsdienste (inkl. Newsletter)	G: E-mail information service (incl. newsletters)
H: Information durch Familie oder Bekannte	H: Information by family or friends
I: Eigene Beobachtung (inkl. Heim-Wetterstationen)	I: Own observations (incl. home weather station)
J: Nein, ich informiere mich nicht gezielt.	J: No, I do not seek information on weather on purpose.

Wie oft beziehen Sie üblicherweise Wetterinformationen aus den genannten Medien? A: täglich B: unregelmäßig mehrmals die Woche C: nur wenn ich etwas plane, was wetterabhängig ist D: nur wenn das Wetter ungewöhnlich erscheint E: selten bis nie	How often so you usually receive information from the sources mentioned above? A: Daily B: Several times a week C: In preparation for outdoor activities D: Occasionally if the weather seems unusual E: Rarely or never
Wie häufig sind Sie persönlich in Berlin in den letzten 12 Monaten von schweren Unwettern (schwere Gewitter, Orkanböen etc.) betroffen gewesen?	How often have you personally been affected by severe weather events (heavy thunderstorms, hurricane-force gusts etc.) in Berlin over the past 12 months?
Wie häufig haben Sie in Ihrer Nachbarschaft (Straße, Kiez) in den letzten 12 Monaten Unwetterschäden feststellen können?	How often have you observed damages resulting from severe weather in your neighborhood over the past 12 months?
Wie häufig sind Ihnen in den letzten 12 Monaten in Berlin Schäden durch Unwetter aufgefallen?	How often have you observed damages resulting from severe weather in Berlin over the past 12 months?
In schwierigen Situationen kann ich mich auf meine Fähigkeiten verlassen.	In difficult situation I can rely on my abilities.
Die meisten Probleme kann ich aus eigener Kraft gut meistern.	Most problems I can solve under my own steam.
Auch anstrengende und komplizierte Aufgaben kann ich in der Regel gut lösen.	Also exhausting and complicated tasks I can normally solve easily.
Ich habe mein Leben selbst in der Hand.	I am in control of my own life.

Wenn ich mich anstrenge, werde ich auch Erfolg haben.	If make an effort, I will be successful.
Egal ob privat oder Beruf: Mein Leben wird zum großen Teil von anderen bestimmt.	Regardless whether private life or job: My life is mostly controlled by others.
Meine Pläne werden oft vom Schicksal durchkreuzt.	My plans are often jeopardized by fate.
Ich habe persönlich gute Möglichkeiten mich und mein Eigentum vor einem drohenden schweren Unwetter zeitnah zu schützen.	I personally have good options to promptly safeguard myself and my belongings against an imminent severe weather threat.
Ich persönlich habe die Möglichkeit mich über drohende Gefahren durch Unwetter rechtzeitig zu informieren.	I personally have good options to inform myself about imminent severe weather threats in time.
Es liegt an mir, mich eigenständig über drohende Gefahren durch Unwetter rechtzeitig zu informieren.	It's up to me to inform myself independently and in time about imminent severe weather threats.
Wie hoch ist Ihr generelles Vertrauen in die Genauigkeit von Wettervorhersagen?	How high is your general confidence in the accuracy of weather forecasts?
Wie hoch ist Ihr Vertrauen in die Genauigkeit einer Wettervorhersage für die kommenden 2 Tage/ 7 Tage bezüglich folgender Wetterphänomene? A: Temperatur B: Niederschlagswahrscheinlichkeit C: Niederschlagsmenge	How high is your confidence in the accuracy of a 2-day/ 7-day forecast regarding...? A: Temperature B: Chance of precipitation C: Amount of precipitation

Wenn die Meteorologen ehrlich über das Ausmaß einer Gefahr sein würden, dann würden sie keine Prozentangaben angeben, sondern eindeutige und feste Zahlen.	If meteorologists were honest about the size of a hazard, they would not use probabilities but one unambiguous number.
Die Angabe von Wahrscheinlichkeiten in Wettervorhersagen geschieht um Unwissen zu verbergen, weil die Situation nicht vollständig erfasst wurde.	Probabilities in weather forecasts are used in order to hide lack of knowledge, because the situation could not be entirely apprehended.
Wenn eine Gefahr durch Extremwetter droht, möchte ich keine Annahmen und Vermutungen hören. Ich möchte wissen, ob es passiert oder nicht.	If severe weather is likely to happen, I do not want to hear assumptions or speculations. I want to know whether it occurs or not.
Ich möchte, dass mir Experten sagen, ob eine Gefahr durch Extremwetter droht, anstatt mir aus den zur Verfügung stehenden Informationen mein eigenes Bild machen zu müssen.	I want experts to tell me whether or not I am threatened by severe weather, instead of having to draw my own conclusions from the information available.
In einer seriösen Wettervorhersage werden eindeutige und feste Zahlen verwendet.	A professional and reliable weather forecast uses single and concrete numbers.
Es wird nur dann eine Wetterwarnung herausgegeben, wenn große Gefahr für die Bevölkerung besteht.	Weather warnings are only issued when there is a high risk for the people affected.
Welches Geschlecht haben Sie? A: männlich B: weiblich C: keine Angabe	Please state your gender. A: Male B: Female C: Prefer not to say
Bitte nennen Sie Ihr Alter in Jahren.	Please state your age in years.

Wie hoch ist Ihr durchschnittliches Haushaltsnettoeinkommen?	What is your average net household income?
A: Kein Einkommen	A: No income
B: unter 500 EUR	B: Less than 500 EUR
C: 500 bis unter 1000 EUR	C: Between 500 and 999 EUR
D: 1000 bis unter 2000 EUR	D: Between 1000 and 1999 EUR
E: 2000 bis unter 3000 EUR	E: Between 2000 and 2999 EUR
F: 3000 bis unter 4000 EUR	F: Between 3000 and 3999 EUR
G: 4000 bis unter 5000 EUR	G: Between 4000 and 4999 EUR
H: 5000 EUR und mehr	H: 5000 and more
I: keine Angabe	I: Prefer not to say
Welchen höchsten allgemeinbildenden Schulabschluss haben Sie?	Which is your highest general school certificate?
A: Schüler/-in	A: Student
B: Von der Schule abgegangen ohne Hauptschulabschluss	B: Left school without certificate
C: Hauptschulabschluss (Volksschulabschluss)	C: Certificate of Secondary Education
D: Realschulabschluss (Mittlere Reife)	D: Secondary School Certificate
E: Polytechnische Oberschule der DDR oder gleichwertiger Abschluss	E: Polytechnic secondary school of the GDR or similar graduation
F: Fachhochschulreife, Abschluss Fachoberschule	F: Advanced technical college certificate
G: Allgemeine oder fachgebundene Hochschulreife	G: Higher education entrance qualification
H: Einen anderen Schulabschluss	H: Any other school-leaving certificate
Wo wohnen Sie? (PLZ)	Where do you live? (ZIP code)
Wie lange wohnen Sie bereits in Berlin?	How long have you been living in Berlin?

A: unter 1 Jahr	A: less than 1 year
B: 1 bis 3 Jahre	B: 1 to 3 years
C: 4 bis 6 Jahre	C: 4 to 6 years
D: 7 bis 10 Jahre	D: 7 to 10 years
E: über 10 Jahre	E: More than 10 years
Wie ist Ihr aktueller Wohnstatus?	What's your current ownership situation concerning your home?
A: Eigentümer	A: Owner
B: Mieter	B: Tenant
Welche Beschreibung passt am besten zu Ihrem Wohnhaus?	Which description best fits your building?
A: freistehendes Einfamilienhaus	A: Detached house
B: Doppelhaushälfte	B: Semi-detached house
C: Mehrfamilienhaus (Reihe)	C: Multi-family house (town house)
D: Wohnblock (mit Seitenhaus ggf. Hinterhaus)	D: Block of flats (may be with rear house)
E: Hochhaus mit mehr als 6 Etagen	E: Multistory building (more than 6 stories)
Zeichnet sich Ihre Wohnung/ Ihr Haus durch eine der folgenden baulichen Zusätze aus?	Does your building feature one of the following structural conditions?
A: Keller	A: Basement
B: Balkon	B: Balcony
C: Garten/Terrasse	C: Garden/ terrace
D: Empfindliche bauliche Zusätze, etwa Photovoltaikanlage	D: Sensitive structural elements like a photovoltaic installation
E: Keine der Genannten	E: None of the above-mentioned

D Means and Standard Deviations of Outcome Variables

Means (in %) and standard deviations of the outcome variables for all four scenario thresholds in order of appearance in the paper.

			Scenario 1	Scenario 2	Scenario 3	Scenario 4
Education	Low	Mean	51.41	49.51	42.99	50.68
		SD	24.39	32.22	27.07	33.93
		N	76	83	71	81
	Mid	Mean	47.77	43.84	41.97	40.91
		SD	25.85	31.17	28.22	32.38
		N	325	390	322	386
	High	Mean	44.89	34.44	38.4	30.68
		SD	23.47	27.62	25.83	27.8
		N	608	677	610	673
Gender	Men	Mean	46.35	38.68	40.97	36.13
		SD	24.33	30.46	26.7	31.21
		N	488	547	490	543
	Women	Mean	46.38	38.9	39.11	35.35
		SD	24.32	29.03	26.46	30.04
		N	544	631	538	626
		Mean	44.33	30.9	38.91	27.37

Age

	18 -24	SD	20.76	24.06	24.31	23.14
		N	118	126	111	125
		Mean	45.09	34.12	37.58	32.08
	25 - 34	SD	20.87	24.6	23.71	26.18
		N	232	248	236	253
		Mean	45.72	37.08	38.04	34.07
	35 -44	SD	25.52	27.55	25.91	27.96
		N	186	225	190	223
		Mean	47.63	41.43	41.87	38.73
	45 - 54	SD	25.14	32.36	27.51	33.81
		N	264	295	260	287
		Mean	49.42	44.07	43.91	39.53
	55- 64	SD	27.05	31.80	29.98	33.15
		N	189	228	186	225
		Mean	39.95	46.88	34.26	45.1
	65 -90	SD	28.23	39.1	26.21	39.44
		N	39	49	42	49
Housing status	Owner	Mean	43.15	35.47	37.57	32.42
		SD	25.81	30.13	27.66	30.83
		N	184	216	188	210
	Tenant	Mean	47.11	39.57	40.5	36.42
		SD	23.99	29.58	26.3	30.45
		N	852	966	844	963
Garden/ balcony	no	Mean	44.91	32.87	36.38	30.49
		SD	22.81	26.3	25.64	28.37
		N	170	188	176	191
	yes	Mean	46.7	39.95	40.7	36.71
		SD	24.65	30.19	26.71	30.86

		N	866	994	856	982
Direct experience	Low	Mean	45.89	37.49	39.01	33.7
		SD	24.52	29.08	26.3	29.56
		N	506	592	512	587
	High	Mean	47.01	42.13	42.95	40.32
		SD	23.86	30.82	27.53	31.55
		N	339	374	329	373
Ability to act	very low	Mean	47.25	44.78	43.86	42.54
		SD	24.73	31.18	28.16	32.32
		N	142	170	134	166
	low	Mean	46.6	36.73	41.13	34.31
		SD	23.72	27.26	26.96	28.52
		N	336	383	334	382
	high	Mean	46.72	39.11	39.87	35.52
		SD	42.21	29.79	25.53	30.27
		N	343	394	353	391
	very high	Mean	45.06	37.45	35.81	33.43
		SD	25.44	31.84	26.23	32.36
		N	215	235	211	234
Trustworthiness	1	Mean	42.15	29.66	33.72	25.22
		SD	22.75	25.16	24.94	26.53
		N	150	157	150	156
	2	Mean	41.54	32.34	35.04	29.02
		SD	21.8	27.39	24.83	28.03
		N	242	277	255	277
	3	Mean	47.89	40.35	41.9	37.07
		SD	24.21	29.29	25.8	30.09
		N	324	387	325	385

		Mean	51.06	44.35	44.57	41.43
	4	SD	25.59	30.91	27.55	30.76
		N	216	244	207	237
		Mean	48.05	48.34	45.37	48.04
	5	SD	28.14	33	31.23	34.96
		N	88	99	82	100
		Mean	34.33	27.45	25.35	24.33
	1	SD	18.16	28.3	19.16	32.71
		N	21	22	20	21
		Mean	41.52	29.48	33.95	27.53
	2	SD	23.47	23.54	24.83	25.91
		N	77	86	79	88
		Mean	43.78	36.69	39.62	34.47
Desire for certainty	3	SD	22.37	28.24	25.65	29.54
		N	244	284	250	283
		Mean	46.83	38.95	39.39	35.2
	4	SD	23.51	29.06	25.31	29.46
		N	398	456	402	451
	5	Mean	49.79	43.4	43.55	40.1
		SD	26.92	32.37	29.28	33.22
		N	292	330	278	326

E Original German of the Interview Quotes in Order of Appearance

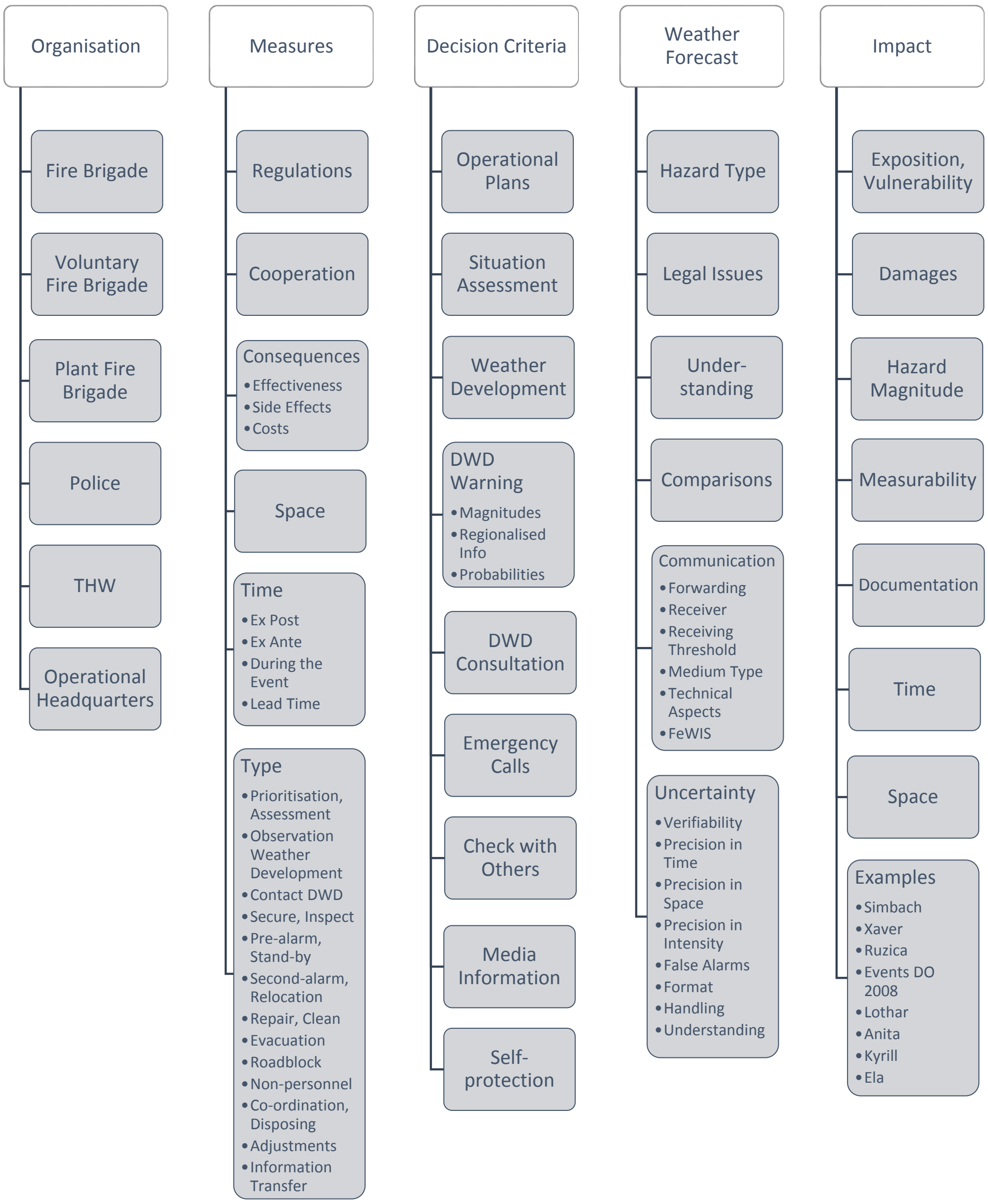
English Translation	Original German Quote
“We are information brokers. We pick up [information] and pass it on.”	“Wir sind information broker. Wir nehmen [die Informationen] auf und verteilen das wieder.”
“We also receive weather watches [. . .]. However, we cannot jump into action with every notice. Only when we have concrete warnings giving us a concrete indication: ok, something is happening sometime soon. . . ”	“Wir kriegen auch Vorwarnungen [. . .]. Wobei wir natürlich nicht gleich bei jeder Meldung die Pferde schnell machen können, sondern nur, wenn wir konkrete Warnungen haben, sodass wir einen konkreten Anhaltspunkt haben: ok, da passiert jetzt was in absehbarer Zeit. . . ”
“The decisive factor is the damage, not the strength of the storm.”	“Entscheidend ist der Schaden, nicht die Stärke des Sturmes.”

"You can call in the volunteer fire-brigades at any time. Of course, you must do that with a certain delicate touch – you may have also realized that on Thursday they were not so happy, because they were not called into action."	"Die Freiwilligen Feuerwehren kriegt man halt immer, die kann man immer in den Dienst rufen. Das muss man natürlich auch mit einem gewissen Fingerspitzengefühl machen – das haben Sie ja vielleicht auch mitgekriegt, dass die am Donnerstag nicht so glücklich waren, weil sie halt dann nicht gerufen wurden, also nicht zum Einsatz kamen."
"...you have to take every [warning] message seriously. When a fire detection system is activated, it is generally assumed that there is a fire and we trigger an alarm immediately. Even if the system triggered false alarms three times on the same day [...]. You have to deal with weather reports quite similarly, you do not know what is happening, you must always take [the consequences] into consideration."	"...man muss jede [Warn-]Meldung ernst nehmen. Bei einer Auslösung in einer Brandmeldeanlage geht man grundsätzlich davon aus, dass es brennt und da wird auch ohne Verzögerung sofort alarmiert. Selbst wenn die entsprechende Anlange am selben Tag dreimal falsch ausgelöst hat [...]. Letztlich muss man mit Wettermeldungen ähnlich umgehen, man weiß nicht welcher Fall eintritt, man muss immer damit rechnen."
"If I get a [warning] message, I start the full program. Then I am also on the safe side."	"Wenn ich eine [Warn-] Meldung bekomme, dann fahre ich das volle Programm ab. Und dann bin ich auch auf der sicheren Seite."
"You can only prepare. Trees cannot be sawn off beforehand for safety reasons. That does not work. And I can only pump water away when it has flooded."	"Man kann sich nur vorbereiten. Bäume lassen sich ja nicht vorher absägen aus Sicherheitsgründen. Das funktioniert ja auch nicht. Wasser kann ich ja auch nur wegpumpen, wenn es überschwemmt ist."

"What is important are the things which [...] represent an imminent threat or disturb infrastructures. Such things must be removed immediately. A tree on a forest path can also be left there for three days. That will not bother anyone much."	"Wichtig sind die Geschichten, die [...] eine akute Gefährdung bedeuten bzw. die Infrastruktur stören. Die Sachen müssen sofort beseitigt werden. Der Baum auf dem Waldweg kann auch drei Tage liegen bleiben, das wird keinen groß stören."
"...if we do not have the necessary means in that situation, then, obviously, we cannot address the missions in time. That's the consequence."	"...wenn wir nicht über die notwendige Menge an Einsatzmaterialien verfügen in der Situation, dann können wir die Einsätze natürlich nicht mehr so zeitnah bedienen. Das ist die Konsequenz."
"The fire brigade's response does not depend on the warning but on the assessment [of the situation]."	"Reaktion der Feuerwehr hängt nicht von der Warnung, sondern von der Einschätzung [der Lage] ab."
"We always try to get a bit ahead of the situation by collecting information, evaluating different networks, to have information early on, preferably before an event..."	"Wir versuchen eigentlich immer so ein bisschen vor die Lage zu kommen, also Informationen zu sammeln, verschiedene Netzwerke auszuwerten, um frühzeitig Informationen zu haben, möglichst vor einem Ereignis..."
"...having an expert explain it properly once again. Is it as I think it is, or will it develop a bit differently? It is more about getting confirmation. We all surely are no [weather] professionals."	"...man sich vom Fachmann noch mal richtig aufklären lässt, ist es denn so, wie ich denke oder entwickelt sich das hier ein bisschen anders? Da geht es eigentlich eher darum, dass man sich noch mal rückversichert. Wir sind ja alles keine [Wetter-] Fachleute."

"And if something is approaching from the west, it would be interesting to know how it looks right now in [name of city]. And if we learn from the control centre that they are being deluged, the chance is relatively high that it will also happens to us. That would be a reliable information."	"Und wenn was aus Westen kommt, dann wäre es interessant zu wissen, wie es in [Name einer Stadt] gerade eben aussieht. Und wenn wir dort schon von der Leitstelle wissen, dass die gerade untergehen, ist die Chance relativ hoch, dass bei uns wohl auch was passiert. Das wäre eine verlässliche Information."

F Interview Codes and Sub-Codes



Selbstständigkeitserklärung

Hiermit erkläre ich, dass ich die vorliegende Dissertation selbstständig verfasst und keine anderen als die angegebenen Hilfsmittel genutzt habe. Alle wörtlich oder inhaltlich übernommenen Stellen habe ich als solche gekennzeichnet. Jegliche Mitarbeit der Co-Autorinnen und Co-Autoren der der Arbeit zugrundeliegenden Aufsätze sind im beigefügten Schreiben der Prüfungskommission kenntlich gemacht und erläutert.

Ich versichere außerdem, dass ich die vorliegende Dissertation nur in diesem und keinem anderen Promotionsverfahren eingereicht habe und, dass diesem Promotionsverfahren keine endgültig gescheiterten Promotionsverfahren vorausgegangen sind.

Berlin, den 5. Juni 2018 Thomas Kox