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Perception and use of uncertainty in severe weather warnings by emergency services in Germany

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ABSTRACT

In the course of the WEXICOM project at the Hans-Ertel-Centre for Weather Research of the Deutscher Wetterdienst (DWD), a survey was conducted in autumn 2012 to question how weather warnings are communicated to professional end-users in the emergency community and how the warnings are converted into mitigation measures.

161 members of emergency services (e.g. fire fighters, police officers and civil servants) across Germany answered an online questionnaire. Questions included user's confidence in forecasts, their understanding of probabilistic information and their perception and use of uncertainty in forecasts and warnings. A large number of open questions were selected to identify new topics of interest, unknown problems, and research gaps in the field of communicating weather information in Germany.

Results show that the emergency service personnel who participated in this survey generally have a good appreciation of the uncertainty of 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 forecast based on low probabilities as basis for their decisions.

This paper suggests that when trying to enhance weather communication by reducing the uncertainty in forecasts, the focus should not only be on improving computer models and observation tools, but also on the communication aspect, as uncertainty also arises from linguistic origins. Here, improvements are also possible and thus uncertainty might be reducible.

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; Weichert, 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.

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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 (Weichert, 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: 96–97). 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) and is called ambiguity (Ellsberg, 1961) or vagueness (Colyvan, 2008).

Ensemble-Prediction-Systems (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 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., 2008) 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 (ABM, 2009; CFI, 2005; Joslyn and Savelli, 2010; Morss et al., 2008; Sink, 1995) or based on psychological experiments amongst university students (e.g. Joslyn and Nichols, 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; Punkka and Rauhala, 2011; Frick and Hegg, 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., 2008). Visschers et al. (2009) point out that only little research has focused on user specific tailored information, while Morss et al. (2008) 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. 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 Deutscher Wetterdienst (DWD) and Fire Brigades in order to identify the key questions and to identify potential experts.

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 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. Questionnaire design

Based on a preliminary work, a semi-standardised questionnaire was designed. 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., 2008; 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.

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 (Table 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 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.

Table 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

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.

3.1. Communication of weather forecasts and warnings

Experts stated that the Deutscher Wetterdienst 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 Ensemble-Prediction-System (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.

3.2. Perception of uncertainty in weather forecasts and warnings

3.2.1. Confidence in weather forecasts and warnings

Confidence in weather forecasts is not directly related to the understanding of forecast uncertainty (Morss et al., 2008). 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. 1).

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

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). 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., 2008).

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

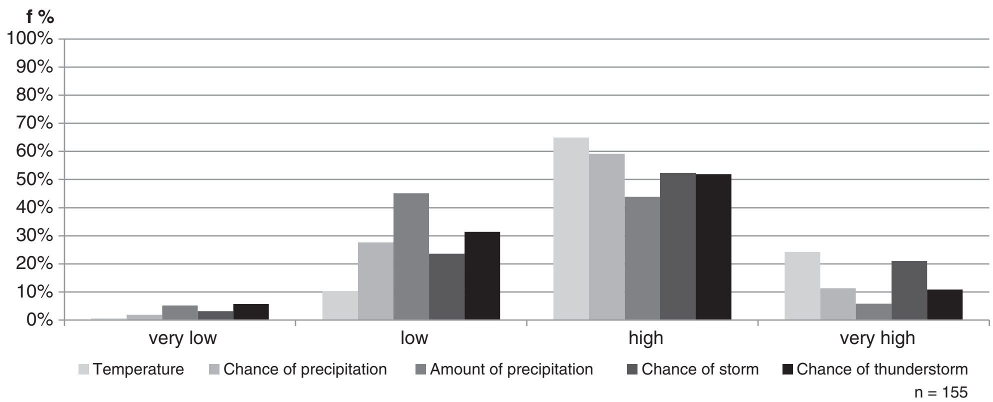

Fig. 1. Confidence in 2-day forecasts ($n = 155$).

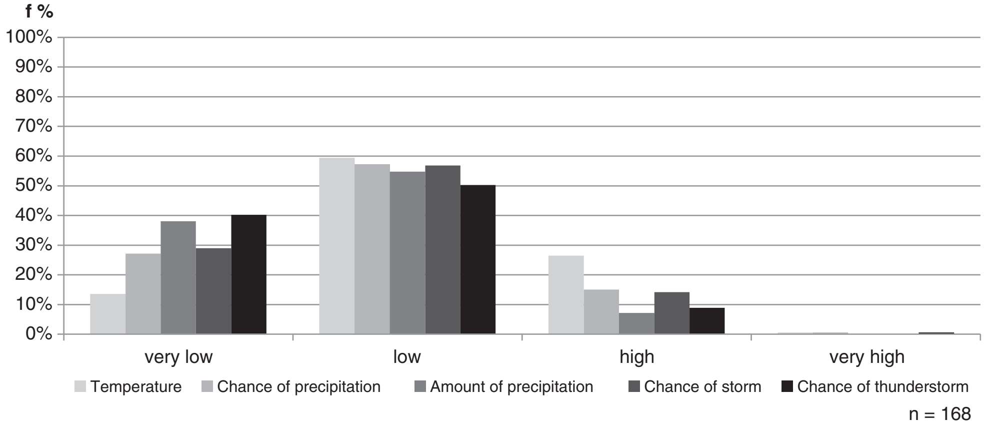

Fig. 2. Confidence in 7-day forecasts ($n = 168$).

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). 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.

3.2.2. 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*" (Gigerenzer et al., 2005). They conclude that the public has to be better educated in statistics. However, Morss et al. (2008) 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*" (Morss et al., 2008).

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., 2008; 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 and Nichols, 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 and Nichols, 2009; Morss et al., 2008).

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. (2008) 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).[1] It is possible that the participants 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 warnings. As briefly addressed above, the 7-day forecast on weather hazards (*Wochenvorhersage Wettergefahren*) uses only verbal statements 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[2] show that nominations scatter extremely (Fig. 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.

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.

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. 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 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

[1] In relative terms (4%, 66%, 30%) these results fit with findings from other studies, e.g. 10%, 59%, 31% in a 2005 study for NOAA regarding laypersons (CFI Group, 2005: 135).

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

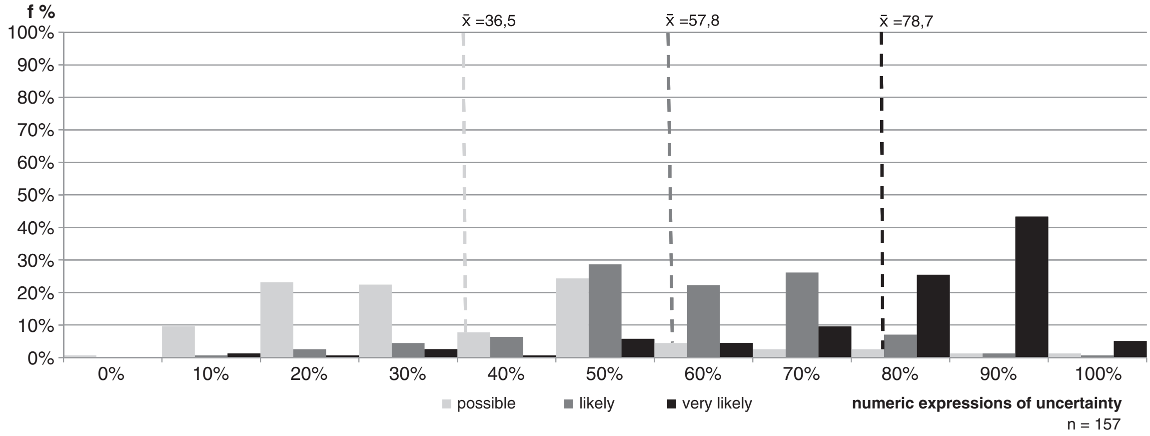

Fig. 3. Numeric associations to verbal expressions of uncertainty (mean values: 36.5% (possible), 57.8% (likely), 78.7% (very likely), $n = 157$).

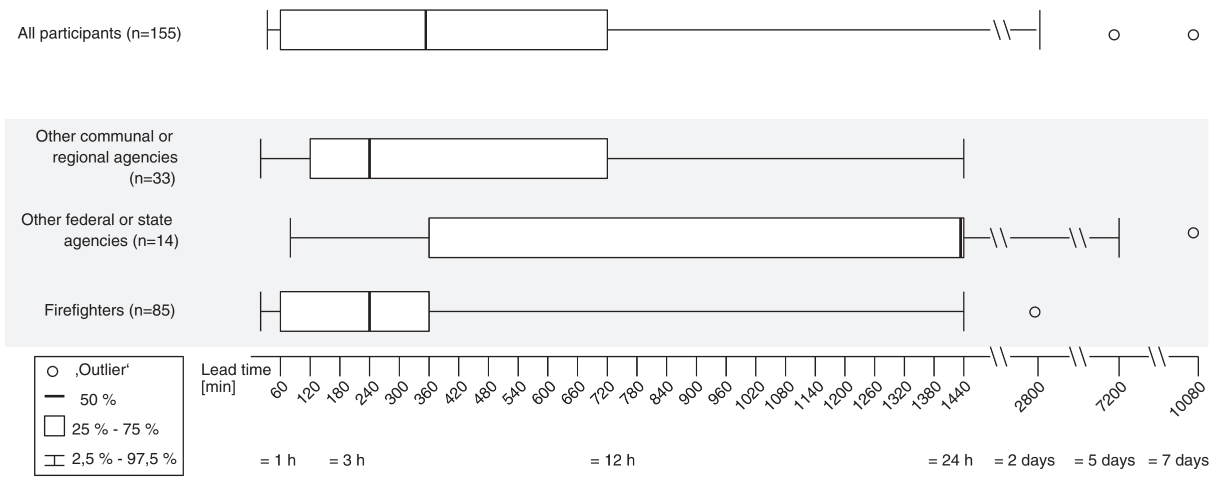

Fig. 4. Organisational lead times needed for preparatory actions (boxplots, all participants and selected subgroups).

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[3] due to information about the probability of occurrence.

This question builds up on the assumption that uncertainty information at an early point 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).[4]

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. 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

[3] 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.

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

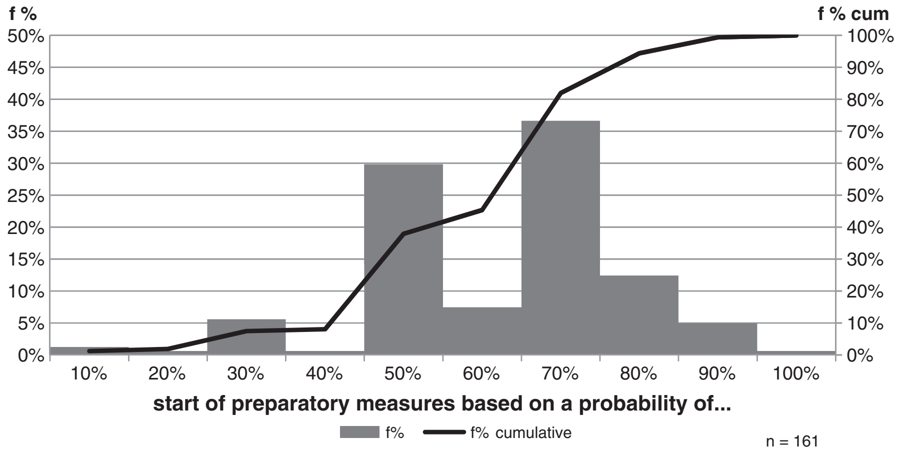

Fig. 5. Preparatory measures based on a probability threshold ($n = 161$).

results and found that users do not want to react to forecasts of low probabilities.[5]

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*". So, such answers should be examined carefully as further ambiguity is involved. There are almost uncountable sources of second-order 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).*" 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.

4. Conclusion

The perception and use of weather warnings have been addressed in several studies in the past, mainly in the USA 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 improving 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. 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

[5] 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).

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.

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Appendix A. Survey questionnaire

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 °C”)
b) Range of values (e.g. “the most likely temperature range will be between 32 °C and 36 °C”
c) Probabilistic values (e.g. “there is a 85% chance of the temperature exceeding 28 °C; a 30% chance of the temperature exceeding 30 °C; a 10% chance of the temperature exceeding 36 °C”)

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)

References

ABM, Australian Bureau of Meteorology, 2009. Public User Survey – Summer 2009. A Report of Research Findings, Melbourne (http://www.wmo.int/pages/prog/amp/pwsp/documents/Public_User_Survey_Report_Summer09_Australia.pdf. Accessed 8 November 2013).

Balzer, K., 1994. On the 'state of the art' in local weather forecasting. Meteorol. Appl. 1 (2), 121–128.

Banse, G., 1996. Herkunft und Anspruch der Risikoforschung. In: Banse, G. (Ed.), Risikoforschung zwischen Disziplinarität und Interdisziplinarität. Von der Illusion der Sicherheit zum Umgang mit Unsicherheit. Ed. Sigma, Berlin, pp. 15–72.

CFI, Customer Feedback Insight Group, 2005. National Weather Service Customer Satisfaction Survey: General public. Report to the National Oceanic and Atmospheric AdministrationCustomer Feedback Insight Group (http://www.nws.noaa.gov/com/files/NWS_Public_survey050608.pdf. Accessed 8 November 2013).

Colyvan, M., 2008. Is probability the only coherent approach to uncertainty? Risk Anal. 28 (3), 645–652.

Demeritt, D., 2012. The perception and use of public weather services by emergency and resilience professionals in the UK: a report for the Met Office Public Weather Service Customer Group.

Demeritt, D., Cloke, H., Pappenberger, F., Thielen, J., Bartholmes, J., Ramos, M.-H., 2007. Ensemble predictions and perceptions of risk, uncertainty, and error in flood forecasting. Environ. Hazards 7 (2), 115–127.

Donat, M.G., Pardowitz, T., Leckebusch, G., Ulbrich, U., Burghoff, O., 2011. High-resolution refinement of a storm loss model and estimation of return periods of loss-intensive storms over Germany. Nat. Hazards Earth Syst. Sci. 11, 2821–2833.

Doswell, C., 2003. Societal impacts of severe thunderstorms and tornadoes: lessons learned and implications for Europe. Atmos. Res. 67–68, 135–152.

Ellsberg, D., 1961. Risk, ambiguity, and the savage axioms. Q. J. Econ. 75, 643–669.

Fahlbruch, B., Schöbel, M., Marold, J., 2012. Sicherheit, In: Badke-Schaub, P., Hofinger, G., Lauche, K. (Eds.), Human Factors, 2 ed. Springer, Dordrecht, pp. 21–38.

Frick, J., Hegg, C., 2011. Can end-users' flood management decision making be improved by information about forecast uncertainty? Atmos. Res. 100 (2–3), 296–303.

Gesamtverband der Deutschen Versicherungswirtschaft e. V., 2012. Naturgefahrenreport 2012: Naturgefahren und versicherte Schäden in Deutschland – eine statistische Übersicht von 1970 bis 2011, Berlin. (http://www.gdv.de/2012/12/versicherte-naturgefahren-in-deutschland-im-statistischen-ueberblick/. Accessed 8 November 2013).

Gigerenzer, G., Hertwig, R., van der Broek, E., Fasolo, B., Katsikopoulos, K.V., 2005. "A 30% chance of rain tomorrow": how does the public understand probabilistic weather forecasts? Risk Anal. 25 (3), 623–629.

Handmer, J., Proudley, B., 2007. Communicating uncertainty via probabilities: the case of weather forecasts. Environ. Hazards 7 (2), 79–87.

Ibrekk, H., Morgan, M.G., 1987. Graphical communication of uncertain quantities to nontechnical people. Risk Anal. 7 (4), 519–529.

Joslyn, S., Nichols, R.M., 2009. Probability or frequency? Expressing forecast uncertainty in public weather forecasts. Meteorol. Appl. 16, 309–314.

Joslyn, S., Savelli, S., 2010. Communicating forecast uncertainty: public perception of weather forecast uncertainty. Meteorol. Appl. 17 (2), 180–195.

Jungermann, H., Slovic, P., 1993. Charakteristika individueller Risikowahrnehmung. Risiko ist ein KonstruktKnesebeck, München 89–107.

Kahneman, D., Tversky, A., 1979. Prospect theory: an analysis of decision under risk. Econometrica 47 (2), 263–291.

Luhmann, N., 2000. Vertrauen. Ein Mechanismus der Reduktion sozialer Komplexität, 4th ed. UTB, Stuttgart.

Mayring, P., 2001. Combination and integration of qualitative and quantitative analysis. Forum Qual. Soc. Res. 2 (1).

Monmonier, M., 2006. Cartography. Uncertainty, interventions, and dynamic display. Prog. Hum. Geogr. 30 (3), 373–381.

Morss, R.E., Demuth, J.L., Lazo, J.K., 2008. Communicating uncertainty in weather forecasts: a survey of the U.S. public. Weather Forecast. 23, 974–988.

Murphy, A.H., 1993. What is a good forecast? An essay on the nature of goodness in weather forecasting. Weather Forecast. 8, 281–293.

Murphy, A.H., 1994. Assessing the economic value of weather forecasts: an overview of methods, results and issues. Meteorol. Appl. 1 (1), 69–73.

Murphy, A.H., Lichtenstein, S., Fischhoff, B., Winkler, R.L., 1980. Misinterpretations of precipitation probability forecasts. BAMS 61 (7), 695–701.

National Research Council, 2006. Completing the Forecast: Characterizing and Communicating Uncertainty for Better Decisions Using Weather and Climate Forecasts. National Academies Press, Washington, D.C.

Palmer, T.N., 2002. The economic value of ensemble forecasts as a tool for risk assessment: from days to decades. Q. J. R. Meteorol. Soc. 128 (581), 747–774.

Pate-Cornell, E., 1996. Uncertainties in risk analysis: six levels of treatment. Reliab. Eng. Syst. Saf. 54 (2–3), 95–111.

Patt, A.G., Schrag, D.P., 2003. Using specific language to describe risk and probability. Clim. Chang. 61 (1), 17–30.

Punkka, A.-J., Rauhala, J., 2011. Use of severe weather outlooks for damage prevention and civil protection in Finland. 6th European Conference on Severe Storms (ECSS 2011), 3–7 October 2011, Palma de Mallorca, Balearic Islands, Spain (http://www.essl.org/ECSS/2011/programme/abstracts/185.pdf. Accessed 8 November 2013).

Richardson, D.S., 2000. Skill and relative economic value of the ECMWF ensemble prediction system. Q. J. R. Meteorol. Soc. (126), 649–667.

Rogell, R.H., 1972. Weather terminology and the general public. Weatherwise 25, 126–132.

Roulston, M.S., Bolton, G.E., Kleit, A.N., Sears-Collins, A.L., 2006. A laboratory study of the benefits of including uncertainty information in weather forecasts. Weather Forecast. 21, 116–122.

Siegrist, M., 2001. Die Bedeutung von Vertrauen bei der Wahrnehmung und Bewertung von Risiken, Stuttgart.

Siegrist, M., Cvetkovich, G., 2000. Perception of hazards: the role of social trust and knowledge. Risk Anal. 20 (5), 713–719.

Sink, S.A., 1995. Determining the public's understanding of precipitation forecasts: results of a survey. Natl. Weather Dig. 19 (3), 9–15.

Spiegelhalter, D., Pearson, M., Short, I., 2011. Visualizing uncertainty about the future. Science 333 (6048), 1393–1400.

Steinhorst, G., 2009. Moderne Verfahren und Methoden der Wettervorhersage. Promet 35 (1-3), 3–11.

Visschers, V.H.M., Meertens, R.M., Passchier, W.W.F., de Vries, N.N.K., 2009. Probability information in risk communication: a review of the research literature. Risk Anal. 29 (2), 267–287.

Wallsten, T.S., Fillenbaum, S., Cox, J.A., 1986. Base rate effects on the interpretation of probability and frequency expressions. J. Mem. Lang. 25 (5), 571–587.

Weichert, P., 2007. Risiko—Vorschläge zum Umgang mit einem schillernden Begriff. Ber. Dtsch. Landeskd. 81 (3), 201–214.

Weingärtner, H., Schickedanz, U., Göber, M., 2009. Wetterwarndienst. Promet 35 (1-3), 30–38.

Zhu, Y., Toth, Z., Wobus, R., Richardson, D.S., Mylne, K.R., 2002. The economic value of ensemble-based weather forecasts. Bull. Am. Meteorol. Soc. 83 (1), 73–83.