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Towards user-orientated weather warnings

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ABSTRACT

National meteorological services are continually working on improvements of their weather and warning information. Based on five workshops with members of the German national meteorological service and with forecast end-users from emergency management, water management, road maintenance, the media, and others, we discuss operational practices regarding the processing of weather information and specific end-user needs. We focus on the question what users' requirements for a warning are and how meteorological services can address the various user needs. Results show that in order to improve weather (warning) communication, spatial and temporal precision, acceptability and comprehensibility as well as identification of relevant information and technical requirements need to be addressed. A new challenge is the inclusion of impact information provided by e.g. emergency services and social media. As we identify opportunities and constraints for future developments, we emphasise the importance of a strong cooperation and a constant dialogue and discussion of needs between meteorological services and end-users to ensure quality of impact-based forecasts.

1. Introduction

As the federal authority entrusted with the issuing of severe weather warnings for Germany, the national meteorological service Deutscher Wetterdienst (DWD) is continually working on improvements of its weather and warning information. Advancements in meteorology and computer science allow new forecast and warning products that shall enhance forecast precision [10]. Another major source of progress is the cooperation with end-users of weather information, i.e. emergency services as well as public and private enterprises such as the media or providers of various infrastructures. Previously the dialogue between meteorologists and end-users of weather warnings and meteorological information was at times sparse, to the point that end-users had to cope with whatever was produced by the meteorological agency. Recent trends changed the relationship between users and meteorologists to be much closer and interactive. This is expressed in the founding of new units at the interface between customers and internal development in meteorological services, such as the Product Development and Costumer Communication Unit at the DWD. The aim of this ongoing dialogue between the meteorologists and users is to improve weather information/warning products for end-users and make them adjustable for their field of activity.

In the following, we will discuss open questions regarding the adaptability of user-centred weather information as "… *forecasting services will have to identify and interact with users of their forecast products, learn about their weather-sensitive decisions, and see how weather forecast information helps those users make their decisions"* [29]. Weather forecast users differ in their needs and requirements towards weather warnings subject to their responsibilities and competences, and several studies suggest that forecasts can be much more useful to users, when they are customised according to users' needs (e.g. [4,5,13]). User-needs and the usefulness of weather information is specific for every single end-user. Useful or good information varies according to the fields of activity an end-user stands for. In an essay on the 'goodness' of weather forecasts Murphy [18] identifies three general kinds of forecast 'goodness' which are used as a starting point here: *Consistency*, *quality*, and *value*. To be *consistent* the (spoken or written) forecast should correspond to a forecaster's best estimate or judgment of the weather situation. The forecast may be inconsistent if it contains (more or less) spatial or temporal specificity, or if the uncertainty in the forecaster's judgment is not properly reflected in the corresponding forecast either in words or numbers. *Quality* relates to the degree of correspondence (or similarity) between forecast and observed events, represented in concepts like bias, accuracy or skill. Finally, *value* relates to an increase in utility for a forecast user as a result of using the forecast [18,24].

But weather forecasts do not possess an intrinsic value in an economic sense [18,19], rather they have a specific value for a user, if he/she takes action and this action avoids or reduces damage costs

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[18–20]. Kox and Thieken [12] add that "*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*." Governmental agencies responsible for safety and security, i.e. fire brigades, are a good example of such an end-user group operating outside of simple cost-loss analysis. On the other hand, end-users from a broader emergency management domain, like road maintenance services responsible for salting streets [26], do have clearer cost calculations. Accordingly, the end-user perspective may vary. Therefore, the question remains as to what users' requirements for a 'good' warning are. Moreover, how can weather warnings better cover the various user needs? In the paper presented here, we address these questions and focus on a more sophisticated end-user group: the emergency management community as an exclusive cooperation partner of national meteorological services not only in Germany.

In the following sections, we first give an overview of the German weather warning system (Section 2), followed by a presentation of the methods and research design (Section 3). We then present the analysis of workshop results concentrating on user requirements (Section 4.1) and derive suggestions for improvements to address these needs (Section 4.2). Finally, we discuss opportunities and constraints of the implementation of new warning tools (Section 5) and draw conclusions (Section 6).

2. State of German weather warning system

To fulfil its central task the DWD operates a complex management system for the generation and distribution of severe weather warnings to all users (emergency management and public). The current system is in principle a three-tiered implementation (Fig. 1), which uses automated processes in combination with the insight of meteorological forecasters. A central aim of the system is to achieve a very high degree of forecast accuracy expressed in terms of only few missed events or false alarms in order to meet the requirements of the emergency management community and the public.

The first tier is comprised of 'early warning information' ("*Frühwarninformation*") which is regularly issued in form of the "*Wochenvorhersage Wettergefahren*" up to six days ahead. Within this tier the level of detail naturally must remain rather low, providing the users with information on expected severe weather events on a nation-wide scale or on states only, mostly in the form of text reports. This information can be employed by end-users to schedule weather-critical processes or heighten awareness, while usually no immediate measures will be triggered. If the forecast of a severe weather event becomes more certain with regard to its forecast probability and the forecasters expectations, pre-warning information ("*Vorwarninformation*") is added in the second tier up to 48 h ahead. It is issued in the form of machine-readable pre-information severe weather ("*Vorabinformation Unwetter*") or the textual warning situation report ("*Warnlagebericht*"). While this information must still be considered rather broad, it is issued individually for each state and can serve as a practical basis for preparatory measures. When it is clear that the expected events reach a necessary level of certainty and severity (expected thresholds for meteorological parameters), actual (severe) weather warnings ("*(Unwetter-)Warnungen*") are issued in the third tier up to 12 h ahead. These warnings are generated by meteorologists on duty assisted by sophisticated automated systems and are bundled within a unique 'warning status' for Germany. The content of this warning status is issued in a common alerting protocol (CAP) format. The warnings are distributed as fax, SMS, Email and via a mobile phone app (Fig. 2). They are available on the websites of the DWD, meteoalarm (the website from Europe's national weather services) and of many national media. In addition, telephone services operated by the DWD allow for oral consultation on present and developing weather situations.

Initially, the meteorological phenomena and not the administrative boundaries define the warning areas. However, the final warning products (third tier) are mapped on to the German municipalities or (rural) districts to provide end-users with a meaningful geographical and political reference. This is also important in the context of administrative measures, which might be triggered by warnings, as the authority to order measures lies with different political bodies on different administrative levels. As an example, the declaration of a local state of emergency may be based on a severe weather warning, which is specifically issued for an administrative area, but the declaration will be actually made by the lower disaster control authority ("*Untere Katastrophenschutzbehörde*"). Due to Germany's federal system, each of the 16 states has its own laws and regulations concerning emergency management, resulting in manifold distributions of responsibilities. In addition, fire brigades operate quite differently. Depending on whether they are responsible for rural or urban areas, they differ in e.g. their number of personnel and equipment, their length of approach routes, or whether they rely mostly on professional or volunteer staff (for further discussion on the German emergency management system, see [8]).

Classified within the scope of the three hallmarks of forecast 'goodness' [18] the warning system of the DWD places an emphasis on '*quality*'. Extensive work is put into place to evaluate the degree of correspondence of all issued warnings to the actual observed weather conditions. '*Consistency*' as a concept is much harder to implement and

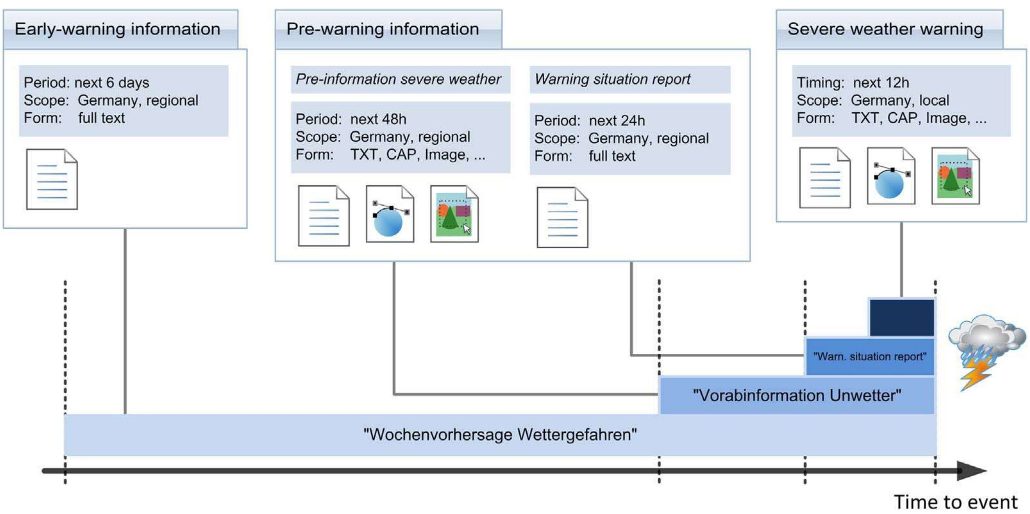

Fig. 1. DWD's three-tiered weather warning system.

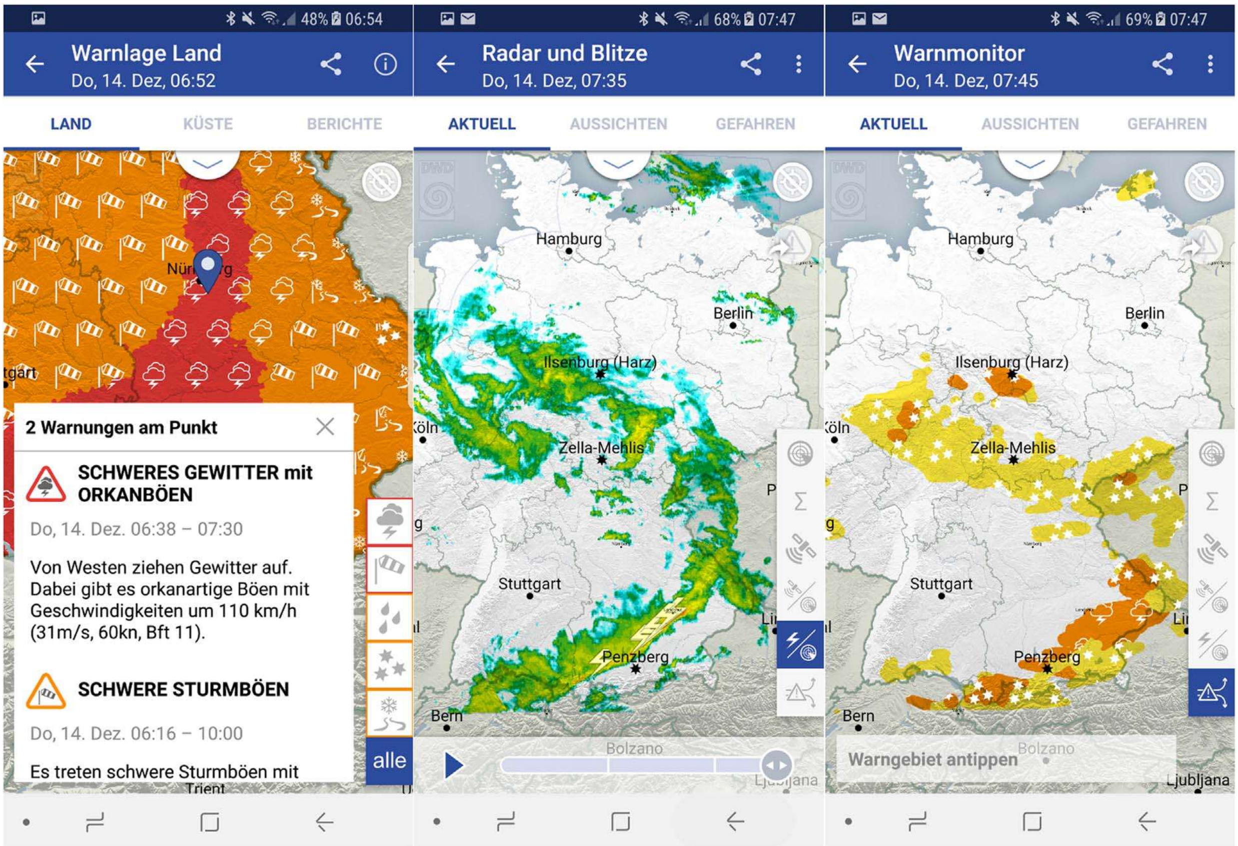

Fig. 2. Example of warning messages via mobile phone app, from left: A severe thunderstorm warning for the Nuremberg region, precipitation radar and lightning, forecasted tracks of thunderstorm cells.

control due to the broad range of user needs. Warnings, as issued today, are to a degree inconsistent in that they do not convey the uncertainty of the forecaster making the warning decision. Within the current 'deterministic' warnings there is almost no room for the communication of uncertainties, as warnings are issued by the forecasters when expected events reach a subjective certainty level. It is assumed that the possible use of probabilistic information within warning messages could potentially increase '*consistency*', as the forecaster is enabled to better communicate the varying degree of certainty associated with each individual warning situation. However, the price of this type of probabilistic information can be the risk of misinterpretation or a lack of understanding within the target group [13,17,9]. The perfect balance remains an open question. The concept of '*value*' probably poses the hardest problem within the scope of severe weather warnings, as it drastically depends on the end-users' needs. A warning message, which is of high value for one user, might be useless for another. Within this context the possibility to tailor warning messages to individual needs [11] and to give access to additional meteorological information are of paramount importance in order to achieve high value for all end-users.

As it is clear that an efficient warning system must take into account the detailed needs of its target groups, user-orientation and research are key concepts for future development of the DWD's severe weather warning system.

3. Methods and research design

The research in this paper is based on a series of five workshops addressing the research questions stated above. The first workshop brought together members of the DWD with members of fire brigades from different German regions to discuss relevant issues concerning current and future weather warnings. The workshop was organised by the research project WEXICOM at Freie Universität Berlin, carried out in the Hans-Ertel-Centre for Weather Research [28]. As part of its ongoing dialogue with key customers, the DWD organised four additional workshops in different places throughout Germany bringing together meteorologists, forecasters and several end-user groups from different

Table 1
Workshop participants.

Place	Date	Participants	Participants' professional backgrounds
Bonn	07./08. Dec 2015	21	Commanding Fire Fighters, Fire Fighter Associations, DWD, Researchers (Science, Social Science)
Essen	07. Sep 2016	22	Commanding Fire Fighters, Road Maintenance Services, Radio Telescope Operator, Solar Park Operator (Research), Water Resource Management, DWD, Researchers (Social Science)
Offenbach	28. Sep 2016	30	Commanding Fire Fighters, Road Maintenance Services, Chemical Plant Operator, Media, State Government Agencies (Internal Affairs, Environment), Finance, Event Organisers
Berlin	03. Nov 2016	22	Commanding Firefighters, Road Maintenance Services, Security Company, Researchers (Science, Social Science, IT)
Hamburg	24. Nov 2016	16	Federal and State Agencies (BSH, Port Authorities, Waterways and Shipping Administration), Maritime S + R, Construction Companies

states who deal with weather related risks, e.g. from emergency management, media, road maintenance services, and outdoor venue operators (Table 1).

All workshops followed a similar participatory approach. They consisted of input talks from DWD scientists and end-users, and group discussions on target issues identified beforehand by the workshop organisers. Therefore all workshops had a transdisciplinary approach, in the understanding that scientists and end-users discuss problems that affect everyone in the group from their respective perspective [3]. The challenging part is that each perspective is based on different terminologies, theories, methodologies and practices. Even prejudices might affect the results in a heterogeneous setting. To address these challenges the discussions followed the concept of 'World Café' [2,27,7]. 'World Café' is a method used to bring together and confront different perspectives leading to an active discussion with combined results. Its objective here was to initialise an open discussion on a shared topic. Depending on the workshop size, participants were divided into groups of five or more persons, with mixed professional backgrounds. Those groups discussed in two rounds on moderated tables with placemats focussing on different topics before they changed tables and thus topics. The discussions covered the topics of warning content and usage, decision-making and evaluation, and future improvement of warnings. Placemats functioned as notepads where participants were encouraged to note down topics, notions and issues important to them during the discussions. Afterwards, the moderators presented results to the whole group and an open discussion with all participants continued. The moderators were asked to collect the minutes on flipcharts, and participants were equipped with pens and cue cards giving them the possibility to erase or change existing aspects or add new ideas. They were finally asked to mark the three aspects on the flipcharts most important to them either with a coloured glue dot or by pen.

The data for a qualitative analysis of the workshops comprise transcripts of audio-recorded discussions, notes taken by participants, pictures of placemats and flip chart posters. All data were analysed in MaxQDA following a structuring content analysis [15]. The aim of this qualitative approach was to reduce the amount of material systematically to the essential content and key aspects of the discussions in an iterative process. Categories were used to systematise the text with respect to the main research questions. They were deductively derived from the research interest and literature outlined above and inductively complemented during the analysis, when new aspects arose from the data.

4. Results from the workshops

Whereas the spatial and temporal consistency and accuracy of a forecast is regarded as an important requirement for warnings, the workshop participants mainly discussed issues of forecast value, though sometimes beyond its sense of utility. In the following subsections, we will outline what weather forecast users from the emergency management community mentioned as requirements towards a 'good' warning (Section 4.1). Several different issues were debated: recognition of spatial and temporal requests, acceptability, relevance of information, comprehensibility, and technical requirements.[1]

Then, we will derive suggestions from the workshop results for how communication of weather warnings could be improved to cover those needs (Section 4.2). We highlight the inclusion and comparisons of (real-time) information (e.g. on actual weather severity) from third parties and users' impact experiences (e.g. traffic disruptions, power cuts), and the importance of cooperation between users and meteorologists.

[1] Please note that the workshop results are not meant to provide a comprehensive list of criteria, but should rather be regarded as an addition to the discussion.

4.1. What are users' requirements towards weather warnings?

4.1.1. Recognition of spatial and temporal requests

Weather is not restricted to administrative domains, and in the case of disasters or extreme events which surpass state boundaries, emergency services of different states may have to work together. The workshop participants were clear that there are few, if any, procedures for extreme weather warning response established in writing or even in legal texts. If they exist, they are only in general terms.

Administrative boundaries can also lead to different access to information even in close-by areas, e.g. if an administrative district is next to a state or national border. In such and other cases, emergency managers may lack information about intensity and impact (i.e. damages, disruptions to infrastructure or daily life) a weather event has had in nearby regions and thus about the potential future impact in their region. Due to the dominance of westerly winds in central Europe, areas west of a region are often affected earlier, e.g. by storms. Participants – both end-users and DWD meteorologists – wish for warnings surpassing such geographical boundaries.

Official weather warnings issued by the DWD often act as a trigger for actions within the end-user community, when they are exceeding a certain warning level (which can vary between organisations). As user needs and required warning lead-time differ, even within organisations, the question remains: When is the best time for either issuing (forecaster perspective) or receiving (end-user perspective) a warning? Experienced users such as fire brigades, who, depending on the season, receive weather warnings daily, stated in the workshops to prefer an intensification of warnings (regarding warning level and time between information) when the event is nearing. Meaning they want to receive a notification with a low probability and subsequent information with a higher probability and more detailed weather information. This is in accordance with the DWD warning system (Section 2). Additionally, emergency managers working mostly during or right after a severe weather event, i.e. fire fighters, stated that weather information about current intensity and expected end of the event are vital as it helps structure operational practices right as the event happens.

Warning lead-time depends strongly on the type of organisation. Participants from fire brigades and emergency managers stated to need a shorter warning lead-time (e.g. Kox et al. [13] report less than 6 h ahead), while participants, e.g. from road maintenance services need longer (more than 12 h ahead). We assume this is mainly due to the organisations' (administrative) area of responsibility and operation, and their temporal expenditure of work tasks to respond to warnings. For instance, while fire fighters' main task might be removing a fallen tree after a thunderstorm, road maintenance services have to drive and salt several kilometres of the Autobahn before freezing rain or snow occurs. Therefore, different warning information is needed at different points in time. Precision in space is slightly favoured over lead-time by emergency services, water management and other users, but road maintenance prefer earliness to precision.

4.1.2. Acceptability

The issue of high false alarm rates and its effects on the reaction to warnings (often referred to as cry-wolf-syndrome) is an often discussed topic (e.g. [1,6,23,25]), which was also intensively discussed in all workshops. Especially when warnings indicate just a low probability of occurrence and are forwarded internally through the emergency management chain, fire fighters are cautious as they expect their staff to pay less attention to warnings in general when they receive them too often. Beside such negative effects on their own staff, workshop participants from the emergency services fear a loss in employers' willingness to excuse their employees for volunteer tasks during working hours, if warnings become more frequent in general without having visible impact in the respective area. They assume that people need to be able to verify warnings for themselves to a certain degree in order to keep believing the warning information they are given. To that effect, emergency managers feel that it is vital to communicate information on real-time impacts in their and nearby regions, e.g. via the media.

4.1.3. Relevance of information

The issue of impacts leads directly to the issue of relevance. For fire brigades this means that relevant information is information on impacts that can be expected. There is currently a debate among scientists and within different national meteorological services if and how impact information should be communicated alongside weather warnings (e.g. [30]). This issue was also extensively discussed during the workshops. Specialised users, e.g. from the solar energy or water resource management sector, see no use in generalised (impact) information as they derive expected impacts for their technical facilities based on their own statistical-dynamical models or experiences regarding past impacts of weather situations. Detailed information about weather development is more helpful to them. More importantly, they need and estimate highly localised probabilities of occurrence and impact scenarios for their own decision-making. However, they constitute a group of specialists with clear-cut responsibilities for mostly small-scale premises. Their needs therefore differ from those of organisations with a more varied range of responsibilities.

By contrast, representatives from fire brigades see benefit from information about expected impacts for their operational planning. As they are mostly reactive in coping with severe weather events, the impacts are of more concern to them than the weather event itself. During the workshops, they stated great interest in what impacts usually occur in a given weather situation in comparison to what for instance has already happened in neighbouring districts in the current weather situation.

While authorities need specific warning contents and specialised users stated no need for impact information, both presumed a need to include impact information when communicating with the public in order to help people assess possible threats from the weather situation at hand. Above all, participants expressly agreed that weather data needs to be related to local conditions, reflecting the local exposure and vulnerability to hazards. One additional advantage of impact information discussed by participants is that experience-based information on impacts are less abstract and easier to handle than abstract warning levels. Especially for the public such information could be helpful to assess the potential threats emerging from given weather phenomena. Participants from the DWD suggested that impact information could prospectively only be included in nowcasting products, thus providing up-to-date reports on current impacts along the weather front. In general, workshop participants from end-user groups agreed that such information should also include which weather phenomena are to be expected, the expected degree of weather intensity and the probability that the next higher warning level will be reached.

4.1.4. Comprehensibility

Participants of the workshop in Bonn acknowledged that knowledge, experience and professional expertise of individuals differ, and not all warning information is suitable for everyone. They proposed that future warnings should address different levels of proficiency concerning weather. At the same time, however, participants stressed that detailed warning information must be accessible to everyone. In the words of one commanding fire fighter at this workshop: '*Herrschaftswissen*' (power of knowledge or elite knowledge), reflecting a hierarchy in knowledge levels between user groups, is not desired in terms of the potential of severe weather events. Therefore, wording (i.e. specialist terms) and figures or diagrams should be used prudently in weather forecasts and warnings.

The workshop participants evaluate the benefits of different display formats of warnings very differently. Some search the warning texts for keywords like 'thunderstorm'. Others prefer a quick overview provided by diagrams which yet others judge as misguiding, because they feel peaks show up in diagrams too prominently. Verbalisations and visualisations in warnings must be unambiguous and consistent. On the one hand, products need to be standardised and simple, as they should be easy to understand also by inexperienced users. In addition, experienced users prefer clear-cut standardised warning information, which facilitate a quick perception of the situation. To this end, consistent wording and universal thresholds in all warning products seem reasonable for some users. On the other hand, some specialised users may need more detailed information that may come in a more technical and specialist terminology not suited for a less experienced audience.

4.1.5. Technical requirements

Requirements towards technical implementation are numerous and diverse. Information and communications technology (ICT) used for disseminating warnings need to be failure-resistant, which is why fax lines remain important as a redundant fallback solution even though new technologies allow for individualisation and information that is more detailed. ICT products used for warnings should be implementable in systems already in use due to security and usability reasons (e.g., keep fax to ensure receipt of warnings).

4.2. How can weather warnings cover various user needs?

The workshops' participatory approach allows both meteorologists and end-users to collaboratively suggest improvements for communicating weather warnings and to satisfy the different user needs and requirements outlined above.

4.2.1. Inclusion and comparison of real time impact information from third parties and users' impact observations

The workshop participants discussed possibilities for using widespread information on actual weather severity (e.g. precipitation amount, wind speed) and impact (e.g. traffic disruptions, power cuts) from social media, from fire brigades' or polices' own units, or other sources such as car on-board computers to have more detailed situation pictures.

One way to aid users to better conceive weather warnings is by providing impact information in weather warnings and compare them with similar events from the near past. They help users to match current information with past events when such information is included in warnings visually, e.g. in diagrams of impacts (e.g. number of emergency calls) with the current event in comparison with a past and comparable event. Therefore, local knowledge about previous impact sites and intensity is important. It can be linked with probabilities of past and current weather events resulting in a local 'impact climatology'. Such an integration of different forms of knowledge calls for a cooperation between forecasters and users.

During the debates, some participants formulated their concerns about how to handle conflicting information from official and non-official sources, which they worried, could lead to a hindrance of operational decision-making, as reliability of sources is hard to assess quickly. If impact information is to be included in forecasts, reports about impacts must come from trustworthy sources. During the discussion at the workshop in Bonn DWD members as well as members of fire brigades therefore preferred their own staff on the ground to act as information sources on local impacts. Nevertheless, during operations fire fighters often have no time to use complex ICT solutions. If they shall act as information sources, they needed a very simple and easy-to-use tool. The idea of a real time impact information system came up which allows fire brigades who are already in operations due to a severe weather event to upload information about impacts in their area. This information is then accessible to other fire brigades, which might also be affected by the same severe weather event, or other emergency managers and DWD forecasters who might benefit from this information in their decision-making. Workshop participants discussed if this may work as a kind of informal social network to enable mutual exchange between departments of different cities and regions in an unofficial and colloquial manner.

4.2.2. Cooperation between users and meteorologists

As not all information (i.e. local and individually desired details) can be included in general warnings due to space limits and a general comprehensibility, the users see personal contact to a regional weather advisor with local experience as helpful for their decision-making. In particular, the participants from fire brigades see a benefit in personal communication and cooperation with DWD forecasters as they have repeatedly experienced their support to explain forecast uncertainties and dissolve misunderstandings.

Although fire brigades are trained in interpreting complex weather information to some degree (e.g. precipitation radar and lightning or forecasted tracks of thunderstorm cells, see Fig. 2), they value meteorologists' experience in dealing with probabilities and knowledge about statistical models for their decision-making. It seems that combined experience of both fire brigades and forecasters will make impact forecasting sensible as it can build on and further existing cooperation. However, not in all regions cooperation between DWD forecasters and local fire brigades is as intense as participants would wish for, giving potential for intensifying such cooperation.

5. Discussion

In order to improve weather warnings in all three dimensions of forecast *'goodness'* a broad range of challenges need to be addressed. At the root of all improvements, a strong cooperation between key users and meteorologists from the DWD in the form of a constant dialogue and discussion of critical needs is an essential requirement. Developments have to be balanced with regard to different user needs, as is obvious in the case of warning issuance lead-time (e.g. in road management vs. emergency services). To allow for a more individualised optimal warning and ensure an optimal forecast for all end-users, further development of the automated warning generation is paramount. In terms of warning efficiency, the number of warnings (updates) may increase if the temporal-spatial resolution is set higher, especially if automatically distributed. Thus, a reasonable balance between compactness and degree of detail (e.g. text and graphics) depending on the user is necessary to prevent information overkill. Therefore, direct communication and an optimal information flow between the DWD and end-users remains an important element, which has to be constantly re-developed. The results show that strong personal interaction between forecasters and end-users is sensible and wished for by both groups. The forecaster's role shifts "*from forecaster to communicator or interpreter*" [29] providing guidance to help the end-user understand the forecast and its uncertainties. With respect to a closer cooperation and the move towards coproduction of information, the end-user's role shifts from pure user to collaborator and partner.[2]

Especially for users within the field of emergency management it is of vital importance to have access to additional weather information that provides the context for the actual warnings. Based on the warning information alone a full preparation of responsive measures is not always possible. Rather, the warning information must be integrated within the individual context of users, which spans a broad field from the public to highly specialized applications such as the offshore servicing of wind farms. Consequently, different users formulate very different needs in terms of lead-time, occurrence probability, spatial resolution, and warning content. In addition to these varying user needs, scientific and technical progress continuously change the general conditions under which warnings are created and distributed. Likewise diverse are the experiences with and the proficiency in integrating weather warnings and forecasts into the decision-making. Some users are quite experienced in the interpretation of complex weather situations, e.g. due to training and the routine use of weather monitoring systems. These users may even base critical decisions directly on warning levels or related weather parameters according to their needs. Others need clear instructions and overall simplification when faced with severe weather information.

Technical innovations, especially in ICT, provide a range of challenges and opportunities in warning delivery. One very prominent challenge is the inclusion of new (impact) information sources such as the inclusion of 'ground truth' data on impacts through, e.g. collaborative digital infrastructures in emergency management for information exchange between on-site-units and control centres [14,21,22], or through the harvesting of social media and user reports in a 'citizen science' approach [16]. However, these new information sources need to be reliable and require extensive testing, verification and quality monitoring, which have to be developed for these new types of data. Alternatively, a trusted user base can help to work around parts of the data consistency problems, e.g. impact reports submitted only by registered emergency management services.

The seamless merge of nowcasting information and numerical weather predictions is another field of development, which would allow for better predictions and warnings on a relevant time scale. A possible generation of impact forecasts also rests on the quality (i.e. spatial and temporal resolution, consistency and accuracy) of the impact information available and could require further complex modelling. Close cooperation with other authorities, e.g. hydrological services, is necessary to initiate these developments, but also administrative challenges have to be overcome, as different warning types are currently issued by a wide range of authorities, without the necessary level of interaction. Any verification of impact forecasts will need new types of observations and thus will be an additional major challenge. The targeted enrichment of warning information with either additional probabilistic information or further details of the expected weather (what has already happened, what is yet to come) remains an important task with regard to the strong connection between warnings and weather. Scenarios and probabilistic details need to be included while at the same time an overall consistent message has to be preserved on all levels of detail. Extensive research, which has to factor in the users' perspective and use of the data, will be necessary in this field to deliver optimised warning products.

6. Conclusion and outlook

The presented results revealed that end-users of forecasts and warnings place emphasis on the *value* aspect of a forecast's *'goodness'*. As the *value* of a forecast is directly linked to their work tasks – and therefore to their responsibilities and needs – information about what impact a weather event might have in their specific domain, is highly important to them. To allow for impact-based warnings, forecasters need to rely on data, which can most sensibly be provided by users. Weather data used for forecasting are high-level scientific data and need to be interpreted skilfully by trained experts. This interpretation work cannot be passed on to end-users with the exception of specialised users who include weather information in their own models. Even though proficient users may have a good understanding of weather, they have other tasks to fulfil especially right before and during extreme weather events. Forecasters have to provide a forecasts' *consistency*. On the other hand, end-users can provide impact data. They are the experts concerning weather impacts in their specific domain. This practical knowledge cannot be gained from meteorological data. Only through cooperation between the meteorological service and its end-users is it possible to ensure *quality* of an impact-based forecast. Consequently, bilateral knowledge transfer between forecasters and users is required in order to bring *value* to impact-based forecasts and warnings. The cooperation between fire brigades and other user groups might be difficult to ensure due to legal concerns and constraints or differences in state laws. Collaboration between the DWD and its end-

[2] As a result, the terminology of 'end-user' would then be open to question.

users, however, is a low threshold activity that can be integrated into established structures. Enhancing mutual exchange via telephone and face-to-face contacts prior, during and in the aftermath of severe weather events can build up trust and help to communicate uncertainty. An ongoing and iterative review of future developments with end-users is important.

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