RAIN – Risk Analysis of Infrastructure Networks in Response to Extreme Weather

Project Reference: 608166

FP7-SEC-2013-1 Impact of extreme weather on critical infrastructure

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Present state of risk monitoring and warning systems in Europe

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Table of Contents

1. Executive Summary

This report (RAIN deliverable 2.3) presents the results of the RAIN task 2.2, the assessment of the predictability of severe weather with current state-of-the-art forecasting systems. For each of the severe weather hazards the present state of risk monitoring and early warning systems is reviewed, potential weaknesses are identified, and recommendations for improvement are formulated. The report covers these weather hazards: Windstorms, heavy precipitation, coastal floods, river floods, heavy snowfall, blizzards, freezing rain, wildfires, hail, thunderstorm gusts and tornadoes.

Methods of research used in this analysis include literature reviews, the carrying out of a survey among European weather services, a survey among critical infrastructure operators, and new own scientific research. The primary focus is on the targeting of warning systems towards the four types of critical infrastructure (CI) covered in the RAIN project: i) roads, ii) railways, iii) electrical power supply infrastructure and iv) tele-communication infrastructure. For each hazard, inventories of the skill and the availability of early warnings with various lead times, ranging from nowcasts to seasonal timescales, have been prepared. In addition, issues related to weather warnings that are not specific to warning products for this sector have been addressed.

The results indicate that predictability and skill (a representation of forecast error) are good and improving for a majority of hazard categories, particularly on timescales between 12 and 72 hours. Less skill and also less interest was found regarding hazards that are complex and local or rare, but potentially have a high-impact: coastal floods, forest fires and thunderstorm-related hazards. It is recommended that European efforts to operationally monitor these hazards for the benefit of national warning authorities and other stakeholders are expanded or initiated. A negligible skill was in general noted for forecasts beyond 10 days, even though some weather services issue products for that time range. The rate of adoption of successful forecasting methods can be improved especially where it concerns weather forecaster training.

Operators of critical infrastructure are seen as an important target group by weather services. In some cases, specialized warning products or strategies have been developed for them and the interest of weather services to cater this sector appears to be on the rise. The adoption of probabilistic forecasts, which convey more information than deterministic (yes/no) forecasts, is slow and the use of such forecasts is an issue that requires further research. Differences between warning thresholds of publicly disseminated warnings between various countries seem not to be based on spatially varying vulnerability. Such unmotivated differences complicate international comparison. More research addressing the relation between warning thresholds and severe weather impacts is needed as well.

A wider public availability of raw meteorological data, warning data and warning verification data by weather services or the European Flood Awareness System will foster research by both academia and private sector to develop innovative tailored warning products. For a successful warning system more effective communication between weather services and CI operators is regarded important. This concerns not only a flow of data and interoperability, but also guidance from a human forecaster regarding model output interpretation and a discussion of different scenarios.

2. Introduction

The RAIN project aims to develop an operational analysis framework that identifies critical infrastructure components impacted by extreme weather events, with the ultimate objective to minimise those impacts.

An important aim of the RAIN project is to assess the short-, medium-range and seasonal predictability of the hydro-meteorological hazards in Europe using state-of-the-art systems. This includes an assessment of their availability and skill. Another important aim of RAIN is to formulate recommendations for the improvement of early warning systems in Europe. Both aims are followed in this report, as can be seen from its structure. For all hazard types a constant outline is provided:

a. Introduction to the hazard type and its peculiarities.
b. Assessment of the available warning systems: Literature review, own research (data analysis and modelling) and analyses of RAIN interviews with weather services. The outcomes include warning levels and thresholds, and an availability table of issued warning products.
c. Predictability of the hazard type in the different time scales. A table with grades for the typical skill (a representation of forecast error) of issued warning products is presented for each hazard type.
d. Recommendations to improve the warning system are outlined, based on the findings.
e. Conclusions abstract the outcome of each of the very different hazard types in this report.

A list of references and further reading is found in the rear section of the document.

The overarching recommendations and conclusions chapter at the end of this report highlights selected findings for each section and invites to further reading.

While the purpose of the RAIN D2.2 report was to present an overview of the way extreme weather impacts on different forms of CI, a key objective here in this RAIN D2.3 report is to look at the provider side of the warning system:

- What types of systematic approaches do weather services offer?
- How widely available are such warning products?
- What can we say about the predictability of the single hazard types and the related product skill?
- Finally, based on our RAIN research, what can be improved?

The RAIN partners were involved in this work according to their field of expertise: The Finnish Meteorological Institute (FMI) addressed snowfall and snow storms, freezing precipitation as well as wildfires. The Free University of Berlin (FU-Berlin) contributed with respect to heavy precipitation and windstorms. The European Severe Storms Laboratory (ESSL) addressed thunderstorm-related hazards, and the TU Delft (TU-Delft) river and coastal flooding. The detailed studies presented in chapter 3 were compiled by the partners – according to their institutions' expertise.

In chapter 4 more general and hazard-independent results of the RAIN weather service survey are presented. The RAIN survey was carried out via online questionnaires in November 2014. The detailed layout of the questionnaire can be found in the Appendix of this report.

Chapter 5 describes the overarching recommendations and conclusions.

Acknowledgement

The authors would like to thank all weather services who have contributed to the research by allowing us to survey them.

We also thank MeteoSwiss and DWD for their agreement to publish model and radar-derived weather map displays of the ESSL Testbed 2015.

In addition, we thank the RAIN internal reviewers for their helpful review of a draft of the report.

3. Risk Monitoring and Warning Systems

This chapter provides a review of the present state of risk monitoring and early warning systems in Europe for each severe weather hazard considered in RAIN. The section includes not only a description of such systems, but also identifies potential weaknesses and formulates recommendations to improve them. In particular, the skill of predictions and their availability to CI stakeholders through specialized and public channels were assessed. In this Chapter, the findings are discussed for each hazard separately because of their strongly differing nature.

Methodology

Before the start of the content-related work for this report, a strategy was developed to ensure that the wide European spectrum of warning systems was optimally reflected. This strategy included not only literature review and extended use of previously retrieved information from RAIN CI stakeholder interviews (described in depth in RAIN D2.2), but also the development and use of a new extensive questionnaire for weather services. In addition, novel scientific research including data analysis and modeling was carried out regarding the predictability of weather systems.

The questionnaire for weather services was provided online. The invitation and request to take part in this online survey was sent out to 55 European weather services (national, regional and commercial/private) on the 30th of October 2014. All known weather services, based on the WMO (World Meteorological Organization) list for national weather services and based on own internet search for other weather services in Europe were contacted per email via direct contact points (where available) or via the official email address. A reminder was sent out to all contact points on the 24th of November 2014.

18 weather services responded to the online questionnaire until the end of 2014, 13 national and 5 private/commercial ones. This sample of answering weather services is slightly over-representative for national weather services. See chapter 4.2 for further details. Also small weather services are over-represented in the answer sample. While the geographical distribution is balanced from west to east in the central and northern parts of Europe, southwest and southeast Europe is under-represented.

Each paragraph contains two tables that identify the availability and skill of warning systems for a specific hazard and for specific forecast ranges. Tables 3.1.2, 3.2.4, 3.3.6, 3.4.2, 3.5.3, 3.6.4, 3.7.2, 3.8.2 and 3.9.2 summarized the “Availability of issued warning products” and Tables 3.1.3, 3.2.5, 3.3.7, 3.4.3, 3.5.4, 3.6.5, 3.7.4, 3.8.3 and 3.9.3 the “Skill of issued warning products”. They contain assessments of skill expressed in qualitatively defined categories. Where the availability and skill of a warning system could not be identified through a review of published scientific findings and for which no specific data could be retrieved from the survey, expert elicitation was conducted among the RAIN experts on the issue.

The four categories for the table “Skill of issued warning products” are:

– “Products not available or useless.”
Useless means that there is no forecast skill that adds value to background climate information.

o “Little use for some applications.”
There is no use for most applications, but for some applications the forecast skill is good enough to add value compared to climatological information.

\+ “Useful, strong additional value compared to mean climate information.”

? “Unknown.”

The four categories for the table “Availability of issued warning products” are:

– “Not available.”

o “Available from some weather services in Europe.”
This is the best estimate for the entity of all weather services in Europe, not only for those surveyed by the RAIN questionnaire.

\+ “Available from many weather services in Europe (standard product). ”
This is the best estimate for the entity of all weather services in Europe, not only for those surveyed by the RAIN questionnaire.

? “Unknown.”

3.1 Windstorms

3.1.1 Introduction

Windstorms associated to extra-tropical cyclones are a prominent feature of the winter climate in Europe. The genesis of these cyclones usually occurs over the North Atlantic or the North American continent along the polar front. The polar front separates cold polar air in the north from warmer subtropical air masses in the south. This temperature gradient provides the energy for the growth of the cyclones. While propagating eastward, the systems intensify depending on the large scale conditions. Under certain conditions a strong intensification can lead to extreme wind speeds, which are able to cause severe damages and fatalities, as the storms reach the European region.

In terms of insured losses the damages caused by windstorms in Europe are among the largest compared to other natural disasters (MunichRe 2000, SwissRe 2000). This is also due to the large areas, which can be affected by individual storms. In many cases critical infrastructure is affected by windstorms. Most damages are caused by falling trees, which can trip power lines and block rails and roads. The consequences are blackouts and the disruption of the transportation system, which again may have impacts on the telecommunication system and emergency operations.

In order to prevent damage or to prepare for response measures after the passage of a storm, precise forecasts are needed. Regarding the forecasts, **timing**, **location** as well as the **intensity** of the event are of importance in order to allow for timely preparations and appropriate allocation of resources. Both public and private weather services developed and apply routines to provide warnings regarding extreme windstorm. These warning systems are assessed in the following section. Finally the predictability of windstorms is analysed.

3.1.2 Assessment of warning systems

The basic information used for warnings of windstorms is provided by numerical weather prediction (NWP) models. These models include a data assimilation cycle, where current observations are merged with the latest model forecasts, in order to obtain a best possible estimate of the current global atmospheric state. This state is used as initial conditions for predicting the future development of the 3-dimensional atmospheric conditions. This procedure is computationally very expensive and usually done by larger national weather services. Smaller public or private weather services often use these model forecasts and refine the data for certain regions of interest with the help of regional models or statistical methods and own observations.

After running the forecast models, experts at the weather services compare and judge the different predictions and, if necessary, issue warnings depending on certain thresholds. In the case of windstorms, these thresholds vary substantially between different countries and weather services (Table 3.1.1). While for example the Slovak Hydrometeorological Institute issues warnings from 12 m/s upwards, at the Czech Hydrometeorological Institute the lowest warning threshold is 20 m/s. Most weather services offer different warning levels with different wind speed thresholds, labelled for example with numbers (1, 2, 3) or colours (yellow, orange, red, purple). Some weather services distinguish between lowlands and mountainous areas (Czech and Slovak Hydrometeorological Institute), others use different thresholds for coastal and inland areas (SMHI). While most services define their warning thresholds based on average wind speeds, the Latvian Environment, Geology and Meteorology Centre uses threshold based on wind gusts. SMHI and the Slovac Hydrometeorological Institute use both average wind and gusts for defining their warning thresholds. The Norwegian Meteorological Institute uses a more flexible approach, where the thresholds depend on the affected area and may also change if other parameters are involved in making the event extreme. For example wind speed in combination with heavy precipitation can lead to more severe damages than extreme winds alone.

Many weather services issue specialized warnings for managers of critical infrastructure. These are addressed mostly towards road management, power transmission and emergency management, but less frequently also for train services and telecommunication. In case of windstorms the meteorological situation is monitored continuously and warnings are issued at any time necessary as well as at scheduled times. The early warning time for windstorms varies strongly between the different weather services (Table 3.1.2). Out of the 15 weather services that issue windstorm warnings, 2 have an early warning time of 18-24 h, 4 of 24-36 h, 4 of 2 days and 5 of 3-5 days.

Table 3.1.1: Warning thresholds for extreme wind speeds of different public and private weather sevices. Numbers in brackets refer to wind gusts, those without brackets refer to 10-minute averaged wind speeds.

Organization	Threshold Value (m/s)	Threshold Name
UBIMET GmbH	20	orange
	28	red
	(42)	purple
SMHI - Swedish Meteorological and Hydrological Institute	average windspeed at sea level	
	14	level 1
	25	level 2
	30	level 3
	gusts inland	
	(21)	level 1
	(25)	level 2
	(30)	level 3
Latvian Environment, Geology and Meteorology Centre	(15)	
	(20)	
	(25)	
	(33)	
KNMI	depending on surrounding weather conditions	
MeteoLux / Administration de la navigation aérienne / L-2632 Findel	18	yellow
	25	orange
	31	red
Icelandic Meteorological Office	20	
	during summer season (May 1st to Sept 15th)	
	15	
ZHMS of Montenegro	17,1	
Lithuanian Hydrometeorological Service	15	
	28	
	33	
DWD (German Weather Service)	(14)	yellow
	(18)	orange
	(29)	red
	(38)	purple
Czech Hydrometeorological Institute	lowlands	
	20	moderate
	25	severe
	30	extreme
	mountains	
	30	moderate
	35	severe
	40	extreme
Slovak Hydrometeorological Institute	lowlands	
	12 (18)	level 1
	16 (23)	level 2
	20 (29)	level 3
	mountains	
	15 (20)	level 1
	20 (26)	level 2
	26 (33)	level 3
Danis Meteorological Institute	24,5	
ZAMG	depending on partner organization, starting from 17m/s	
BLUE SKY Wetteranalysen	15	
Geo-Meteo	15	
Norwegian Met. Institute	25-30 (depending on area)	
	Other thresholds for gusts or when a combination of	

Table 3.1.2: Availability of windstorm warnings.

Availability of warning products (issued products)	Windstorms						
Forecasting ranges according to WMO	0 – 2 h, Now-casting	2 – 12 h, Very Short Range Fore-casting	12 – 72 h, Short Range Fore-casting	72 – 240 h, Medium Range Forecasting	10 – 30 d, Extended Range Fore-casting	1 – 3 m, 3 Month Outlook, Long Range Fore-casting	3 m – 2 y, Seasonal Outlook (departure from climate values)
Public warning products at a given schedule	+	+	+	o	-	-	-
Public warning products and updates issued at any time necessary (24 h continuous monitoring)	+	+	+	?	-	-	-
Tailored warning products for CI customers at a given schedule	+	+	+	?	-	-	-
Tailored warning products and updates for CI customers issued at any time necessary (24 h continuous monitoring)	+	+	+	?	-	-	-
Communication with CI customers on a case by case basis (no fixed agreement)	o	o	o	?	-	-	-
Routine general forecasts (no products for extreme weather events)	+	+	+	+	o	o	o

Source of WMO definitions: "DEFINITIONS OF METEOROLOGICAL FORECASTING RANGES", retrieved on 30 March 2015: http://www.wmo.int/pages/prog/www/DPS/GDPS-Supplement5-AppI-4.html

Availability categories:

-	Not available.
o	Available from some weather services in Europe.
+	Available from many weather services in Europe (standard product).
?	Unknown.

3.1.3 Predictability

Introduction

Many studies are available regarding the predictability of tropical cyclones. Although the mechanisms responsible for the generation and development of tropical and extratropical cyclones are different, they share similar characteristics. Both are cyclonic systems which cause extreme wind speeds and can be tracked in time. Therefore, the methodologies used in studies on the predictability of tropical cyclones should not be neglected here. It can be beneficial to assess these methodologies and to learn from them in order to improve the analysis of extra-tropical cyclone predictability. Therefore, in the following part we will first review some general issues of tropical cyclone prediction and then have a more specific look at the predictability of extra-tropical cyclones.

Tropical cyclones

When predicting windstorms caused by tropical or extra-tropical cyclones, there are basically two approaches. One is to predict the temporal development of the spatial wind fields, usually on a two-dimensional grid. The other approach is to reduce the information of the spatiotemporal fields, which include all available information about a storm, to the track of the storm system. The track of a storm connects the positions of the storm centres at consecutive time steps. The use of such tracks is an important tool for statistical analyses, because a large amount of information is condensed into a format, which is relatively easy to process. Leslie et al. (1998) attempt for example to estimate the inherent limits of tropical cyclone track position errors. It was assumed before that cyclones are to some extent inherently unpredictable due to their chaotic behaviour. They compare these estimates with the position errors currently being obtained in practice at weather centres around the world. It was found that the difference between the inherent and practical limits of tropical cyclone track position errors in the most recent data with improved models and new data assimilation techniques amounts to about 30 to 35 per cent. This suggests that there is still room for improvements.

Although Leslie et al. (1998) studies a general inherent limit of cyclone predictability, the forecast uncertainties of different storms can be very different. How predictable a certain event is depends strongly on the actual atmospheric conditions. In order to estimate the uncertainty of a specific forecast, ensemble prediction systems (EPSs) are run operationally at large centres like the European Centre for Medium-Range Weather Forecasts (ECMWF). In an EPS a numerical weather prediction (NWP) model is run several times, each time with slightly different initial conditions. Those initial perturbations cause the atmospheric conditions in the single model runs, so called ensemble members, to spread apart with increasing forecast time. The size of this spread is a measure of the uncertainty of the forecast. Goerss (2000) showed that ensembles of cyclone track forecasts can significantly improve the forecast errors and he also showed that the spread can help to assess the confidence in the forecast.

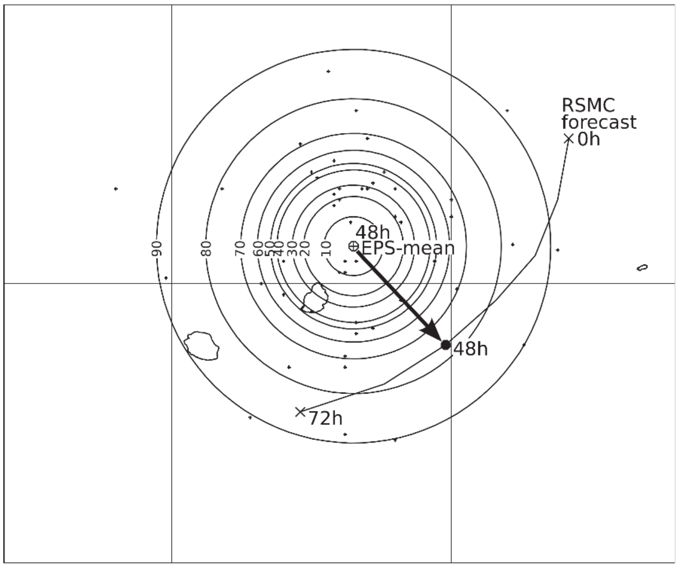

Figure 3.1.1: Example of the construction of the distribution of forecast position probabilities at a given forecast lead time (here 48 h). The official RSMC forecast track is plotted in black, with the forecast position at 48 h indicated by a boldface black dot. The radii of the circles of different probabilities (%) are deduced from the n EPS positions (small crosses). The translation of the probability circle centers to the official Regional Specialized Meteorological Centre (RSMC) forecast position is represented by the black arrow. From Dupont et al. (2011).

Majumdar and Finocchio (2010) use forecasted cyclone track positions. They test the ability of global ensemble prediction systems to predict tropical cyclone track probabilities by defining concentric probability circles around the track positions of the cyclones predicted by the ensemble at a certain time step. The probability circles are defined in a way that the X% probability circle includes X% of the cyclones, which are forecasted by the different ensemble members at a particular time step. The authors show that at lead times between 24 and 84 h the observed cyclone centres lie within the 67% probability circles of the EPS forecasts in roughly 67% of all cases. That means that the spread of the ensemble represents the actual uncertainty of the forecasts. However, at lead times of 96 h and beyond the ensemble was under-dispersive, meaning that the probability circle was too small and the ensemble underestimated the forecast uncertainty.

Dupont et al. (2011) use a similar way to estimate the uncertainty circles from an ensemble, however the centres of these circles are then translated in space towards the position of the more accurate track position from the official Regional Specialized Meteorological Centre (RSMC) forecast (Figure 3.1.1). Thus, the ensemble only provides the uncertainty information, while the track position itself is derived from the independent official forecast.

Extra-tropical cyclones

Froude (2009) evaluates extra-tropical cyclone predictions with the ECMWF EPS in different regions. He uses different matching criteria to compare forecasted cyclone tracks to the tracks derived from the ECMWF analyses. The tracking was based on the 850-hPa relative vorticity fields. They find that cyclone intensity is generally over-predicted over oceans and under-predicted over land. The along-track error, which describes the accuracy of the predicted propagation speeds, is twice as large as the cross-track error, which describes the accuracy of the predicted direction of the storms movement. Differences in forecast accuracy between land and ocean are attributed to the use of different observation systems (radiosondes on land and satellites over oceans).

Froude (2010) compares the predictability of extra-tropical cyclones on the northern hemisphere in nine different ensemble prediction systems run at different weather services. The forecast accuracies of cyclone position, intensity, and propagation speed show large differences between the various EPSs. The spatial resolution of the EPSs has a strong impact on the forecast errors. Systems with a low resolution are not able to accurately model the tilted structure of the cyclones, which is essential for cyclone growth and decay. The EPSs are in general much more under-dispersive for cyclone intensity and propagation speed than for cyclone position. That means that the spread of the ensemble is too small compared to the uncertainty of the forecast. All EPSs under-predict the propagation speed.

In a number of case studies the forecast skill of the ECMWF EPS is analysed for different extra-tropical cyclones, which caused extreme windstorms. Buizza and Chessa (2002) analyse the prediction of the explosive development of a windstorm, which caused serious economic disruption and loss of lives at the east coast of the United States in January 2000. They compared the higher resolved deterministic forecast to the lower resolved ensemble forecast. The ensemble indicated the possibility of a storm hitting the affected area already 2 days before the event, while the deterministic forecast gave skilful predictions only 36 h before the event. They conclude that the way the perturbations of the ensemble members are applied is essential for having members correctly predicting the storms. In particular the use of stochastic parameterizations in addition to the perturbation of the initial conditions had a positive impact on the EPS performance.

The forecasts of three severe storms that caused severe damage in Europe in December 1999 were analysed by Buizza and Hollingsworth (2002). The first storm affected mainly Denmark, while the other two crossed France and Germany. The results indicate that the EPS is a valuable tool for assessing quantitatively the risk of severe weather and issuing early warnings of possible disruptions. They show that an increased resolution enhances the ensemble performance in predicting the position and the intensity of intense storms. The EPS is particularly useful, if in parallel the successive deterministic forecasts show large inconsistencies. EPS forecasts issued on successive days confirm or refine previous forecasts in a more consistent way than the deterministic ones. However, the performance of the EPS was different for the three storms, depending on the meteorological situation. The occurrence of the first storm, which was caused by a large-scale cyclone, was indicated by the EPS already 132 h before the actual event. In case of the other two storms, which were rather small and fast moving systems, the EPS could only give useful indication 72 to 48 hours before the event, while the deterministic forecast did not give any useful indications.

Finally, three major European winter storms are re-forecasted and analysed regarding the skill of the deterministic (Jung et al. 2004) and probabilistic forecasts (Jung et al. 2005) at the ECMWF. The analysed storms are the Dutch storm of 1 February 1953, the Hamburg storm of 17 February 1962, and the storm that hit south England and north-west France during the night of 15/16 October 1987, called the Great October Storm. While the Dutch and the Hamburg storm belong to the pre-satellite era, satellite observations were available for the Great October Storm. The deterministic forecasts for the first two storms turned out to be surprisingly skilful. Indications for these storms have been found at lead times of 48 and 84 h, respectively. The good coverage of the North Atlantic with radiosonde measurements taken from weather ships may explain the skill of those forecasts in the pre-satellite era. These ship measurements, which were not continued in later years, might have been able to capture the development phase of the cyclones on the North Atlantic. Furthermore, the majority of the ensemble members forecast the Dutch and Hamburg storm between 48 to 84 h before the event, respectively. It is argued that reliable warnings could have been issued in these two cases. In case of the Great October Storm the high resolution deterministic forecast could capture the intensity and the track of the event, while the timing was difficult to predict. In this case, the ensemble forecast was able to capture the uncertainty related to the timing of the storm. Reliable forecasts could have been issued 96 h in advance.

Windstorms associated to extra-tropical cyclones

As shown above, Froude (2009, 2010) studied the predictability of extra-tropical cyclones. However, these studies analyse cyclone tracks based on the potential vorticity fields. Therefore, there is no direct relationship to the wind speeds caused by the cyclones. Leckebusch et al. (2008) introduced a tracking algorithm that identifies and tracks wind fields of extra-tropical cyclones. The algorithm is based on exceedances of the local 98th percentile. Therefore only those windstorms are regarded, which have the potential to cause damage.

This impact based windstorm tracking algorithm was applied by Osinski et al. (2015) to identify the windstorm tracks in the ECMWF EPS. The windstorms identified in the different EPS ensemble members are matched with storms identified in the ERA-interim reanalysis dataset (ECMWF ReAnalysis, a global atmospheric reanalysis from 1979, continuously updated in real time).

The authors differentiate between “modified” EPS storms, which have a matching counterpart in the ERA data, and “pure” EPS storms, where no match can be found. In order to be called a match, an EPS and an ERA storm track must have at least 3 overlapping time steps, the distance between the

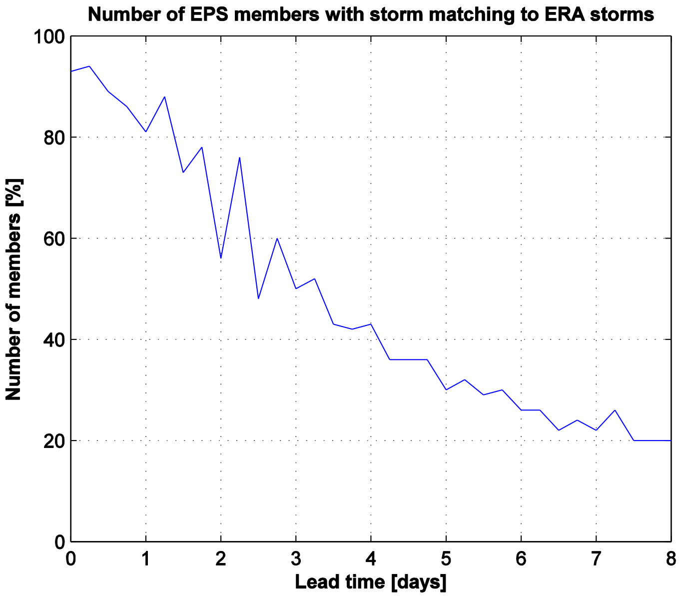

Figure 3.1.2: Median number of EPS members that produce a storm that matches to an ERA storm at different lead times. The lead time refers to the time between the initiation of the forecast and the first time step of the individual

track centres at the first three overlapping time steps must be less than 1500 km, and the first time steps of the two tracks must not lie further apart than 18 h.

The large number of storms in the EPS is shown to reduce the uncertainties related to the statistical distributions of e.g. storm severity, storm size and storm duration. The sparse ERA-Interim sample alone was not sufficient to adequately represent the characteristics of these parameters.

In the following analysis, which was done for this report, we use the ECMWF EPS windstorm catalogue from Osinski et al. (2015) to analyse the predictability of windstorms. The analysed data includes 364 10-day forecasts, each with 50 ensemble members, which were issued between the 1st Oct 2006 and the 31st Mar 2007 at 00 and 12 UTC. As a reference we use windstorm tracks derived from the ERA-interim reanalysis (Dee et al. 2011). The area covered by our analysis includes Europe and part of the North Atlantic. During the analysis period, 61 windstorms are identified in the ERA data and in total 60995 windstorms are identified in all of the ensemble forecasts.

As a first step, we checked for each ERA storm in the analysed time period, how many members of the EPS produce a matching storm. The number of matching EPS storms per ERA storm is analysed for different lead times. The lead time here refers to the time between the initialization of the individual EPS forecasts and the first time step of the ERA storms. At a lead time of 0 days (i.e. the forecast starts on the first time step of the ERA storm) on average more than 90% of the EPS members produce a storm that fulfils the matching criteria (Figure 3.1.2). The number of members that produce matching storms decreases with increasing lead time. At lead times of 3.5 days and more, less than 50% of the EPS members produce a storm that matches to a storm in the ERA dataset. That shows that the EPS is able to predict windstorm occurrence with a rather high certainty in the short range and still gives reasonable indications for the possibility of an upcoming storm in the medium range.

The approach of searching for EPS storms matching to ERA storms does not take into account false alarms, i.e. it neglects the so called “pure” EPS storms, which occur only in the EPS forecasts, but have no matching counterpart in the ERA dataset. To include also “pure” EPS storms, we approach the problem from a forecasting point of view. The real development of the atmospheric situation, which is in our cast represented by the ERA storms, is unknown at the time when the forecast is

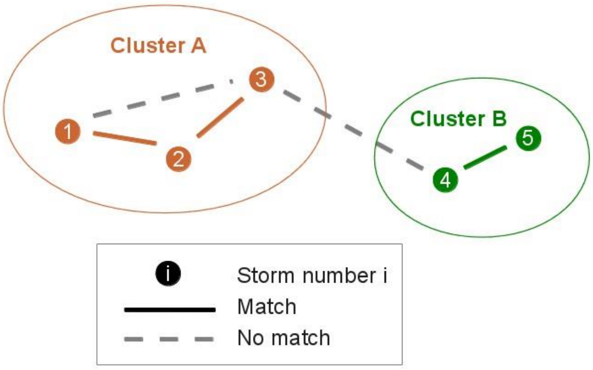

Figure 3.1.3: Schematic view of the storm clustering procedure.

issued. Therefore, the EPS storms in the different members of a forecast should be clustered without taking into account the ERA storms. In this context, clustering means to group EPS storms from different members in a way that each storm of a certain cluster can be regarded as different realization of the same storm. The clustering of storms in a particular EPS forecast is done in the following way: Each EPS storm in each member is compared to each storm in all other members. Each pair of storms is checked for a match or no match by applying the matching criteria described above. After all possible pairs have been checked, all storms that are linked via the matching criteria are said to belong to the same cluster (Figure 3.1.3). For each cluster a mean track can be calculated by averaging the longitudes and latitudes of the track positions of the individual storms at each time step. As an example, the individual tracks of all ensemble members, as well as the derived clusters and their mean track are shown for one particular EPS forecast, which was initialized on the 10th Jan 2007 at 00 UTC (Figure 3.1.4 left). The vertical axis is the time axis, with the initialization of the forecast at the bottom and 10 days after initialization at the top. Each colour represents a particular storm cluster. The figure shows a series of storms crossing Europe during the time of the forecast.

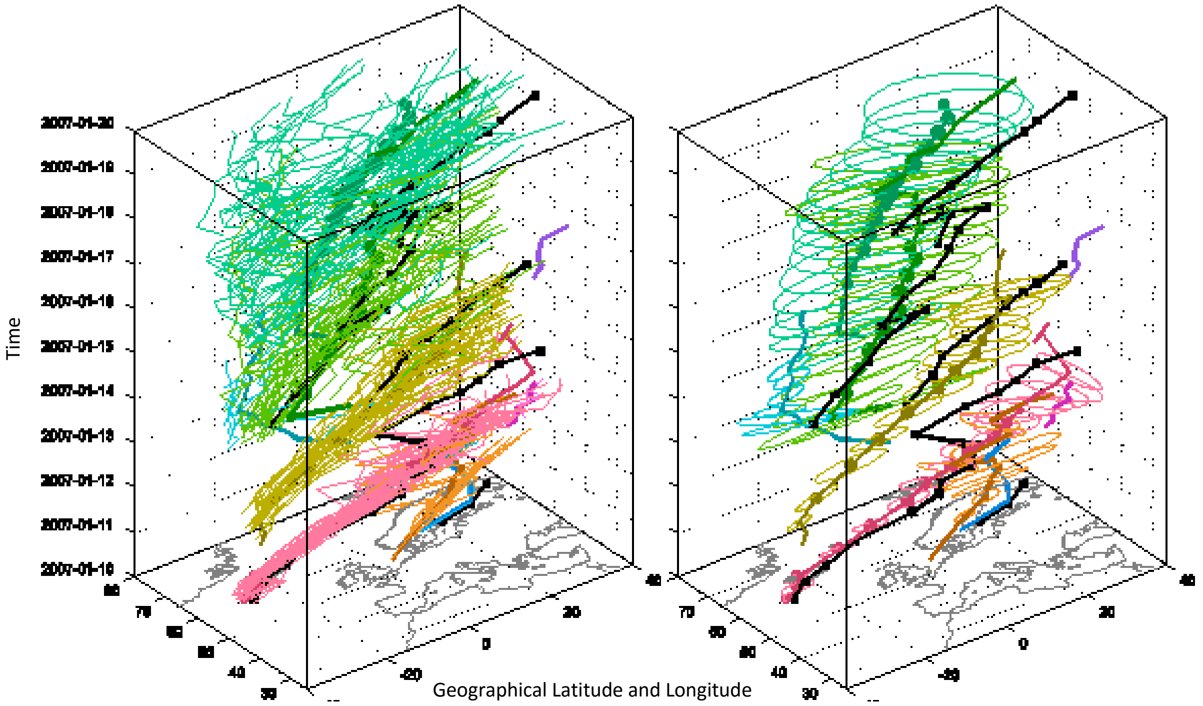

Figure 3.1.4: Windstorms in EPS forecast initialized on the 10th Jan 2007 00 UTC. Colors represent clusters of different realizations of the same storm. Thick lines represent the mean track of the cluster. The size of the colored dots represents the number of members that show a track at a particulater 6-hourly time step. (left) Individual tracks of all members (thin lines). (right) Elypses represent the area of a bivariate normal distribution fitted to the track positions of each cluster at a certain time step, that contains 50% of the probability density. Black lines show the windstorm tracks in ERA-interim.

After calculating the mean cluster tracks in all forecasts issued between October 2006 and March 2007, all clusters in each forecast are compared to the ERA storms. Now, it is checked for each EPS storm cluster if there is a matching ERA storm. The results are shown depending of the lead time, where lead time here refers to the time between the initialisation of the EPS forecast and the average of the first time steps of all tracks related to the storm clusters. If all storm clusters are included in the analysis, at lead time 0 days 80% of all EPS clusters have a matching ERA storm

(Figure 3.1.5, black line). That means on the other hand that 20% of all EPS clusters are “false alarms”. The same analysis is done after dividing the EPS clusters into those which include more than 25 storms and those with less than 25 storms (red and blue lines, respectively). Those which include more than 25 storms have a much higher number of matching ERA storms than those which include less than 25 storms. That shows that if many members produce a storm, it is less likely to be a false alarm.

It was mentioned before that concentric probability circles are often used to describe the spatial uncertainty of hurricane track positions in ensemble forecasts (e.g. Majumdar and Finocchio 2010, Dupont 2011). However, the spatial distribution of the track positions at a certain forecast time is not necessarily concentric, but is in many cases stretched in a certain direction. In order to estimate the spatial uncertainty of the windstorm tracks and, at the same time, account for the non-uniform spatial distribution of the track positions, a bivariate normal distribution is fitted to the track positions to estimate corresponding two-dimensional probability density function (PDF). These PDFs are estimated for every 6-hourly time step of each EPS storm cluster, which was previously identified. From the PDF the area is derived, that contains 50% of the probability density, i.e. 50% of the forecasted windstorm tracks. As an example, this area is shown in Figure 3.1.4 (right) as thin lines in shape of ellipses. The ellipses are stretched in the direction of the largest uncertainty of the track positions. In the example the size of the ellipses gets larger with increasing lead time, as the spatial uncertainty of the track forecasts increases. The average area of the 50% probability ellipses is calculated for all time steps of all EPS storm clusters in all EPS forecasts for different lead times. The area increases almost linearly from around 80,000 km² (roughly the size of Ireland) at forecast initialization to 1,800,000 km² at 8 days lead time.

In a next step one could estimate how reliable the EPS uncertainty areas are. In a perfect ensemble, in 50% of the cases the ERA storm should lie within the area containing 50% of the probability density. Furthermore, a more detailed comparison of the intensities of the EPS storms and the ERA

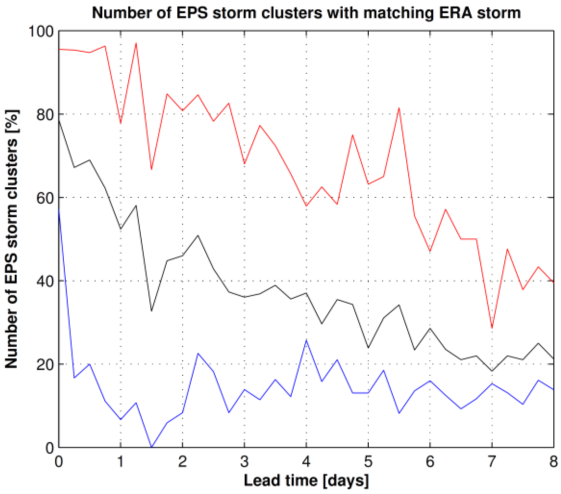

Figure 3.1.5: Number of EPS storm clusters that have a matching ERA storm, depending on the lead time. Lead time refers here to the time between the initialization of the EPS forecasts and the average starting date of all tracks related to the individual clusters. The results are shown for all EPS cluster (black), for all EPS clusters with more than 25 associated storms (red) and less than 25 associated storms (blue).

storms has to be made.

Seasonal prediction of windstorms

Several studies address the seasonal predictability of tropical cyclones (e.g. Gray et al. 1992, Vitart 2006, Vitart et al. 2007). However, only few studies address the seasonal predictability of windstorms caused by extra-tropical cyclones (Renggli et al. 2011a). In general, seasonal predictability is known to be lower in the extra-tropics than in tropical regions (Kushnir et al. 2006). However, it was shown that there is skill in seasonal predictions of mid-latitude teleconnection patterns like the North Atlantic oscillation (Rodwell and Folland 2002). Furthermore, significant correlations exist between the wind storm climate and hemispheric factors like North Atlantic sea surface temperature and sea ice, continental snow cover extent and the North Atlantic Oscillation. Thus, such hemispheric factors or remote effects of tropical variations, like the El Nino Southern Oscillation, which have a high seasonal predictability, could be sources for predictive skill related to European windstorms. In fact, Renggli et al. (2011a) have found small but statistically significant skill of predicting European windstorm frequencies and even suggest an economic usability of the predictions. On the other hand, no significant skill has been found for predicting windstorm intensities. Improvements of the ocean-atmosphere coupling in seasonal prediction models could help to enhance the predictive skill on seasonal time scales (Renggli 2011b).

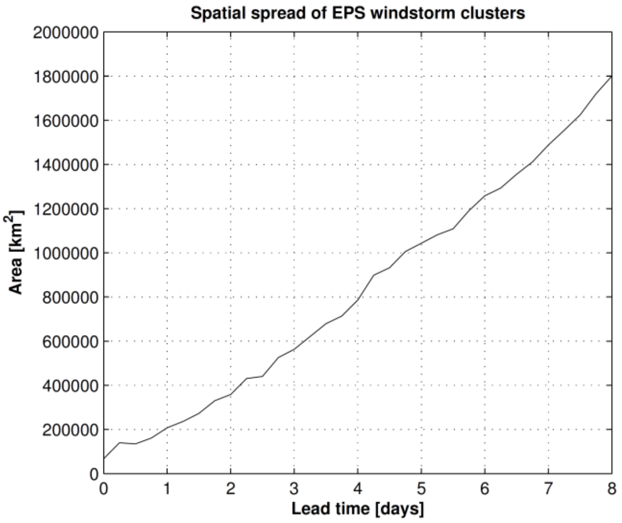

Figure 3.1.6: Average spatial uncertainty of track positions of EPS storm clusters depending on the lead time. The spatial uncertainty is represented by the area that contains 50% of the probability of a two-dimensional normal distribution fitted to the track positions of a certain EPS storm cluster at a certain time step.

Summary

Interviews, reviewed literature and the analysis of the predictability of windstorms suggest that windstorm warnings are, in general, useful in the short range of up to around 3 days (Table 3.1.3). In the medium range of up to 10 days ensemble forecasts can give indications of the possibility of windstorm occurrence. On longer time scales forecasts are not suitable to issue windstorm warnings.

Table 3.1.3: Typical skill of windstorm warnings.

Typical **Skill** of warning products (issued products)	Windstorms						
Forecasting ranges according to WMO	0 – 2 h, Now-casting	2 – 12 h, Very Short Range Fore-casting	12 – 72 h, Short Range Fore-casting	72 – 240 h, Medium Range Forecasting	10 – 30 d, Extended Range Fore-casting	1 – 3 m, 3 Month Outlook, Long Range Fore-casting	3 m – 2 y, Seasonal Outlook (departure from climate values)
Public warning products	+	+	+	o	-	-	-
Tailored warning products and updates for CI customers from land transport sector	+	+	+	o	-	-	-
Tailored warning products and updates for CI customers from energy sector	+	+	+	o	-	-	-
Tailored warning products and updates for CI customers from tele-communication sector	+	+	+	o	-	-	-

Skill categories:

-	Products not available or useless.
o	Little use for some applications.
+	Useful, strong additional value compared to mean climate information.
?	Unknown.

3.1.4 Recommendations to improve the warning system

There are basically three stages related to windstorm warnings. First, making a forecast by using for example NWP models; second, the interpretation of these forecasts by experts and the issuing of warnings after applying certain warning thresholds; and third, the interpretation of the warning by the end user. Each of these stages related to windstorm warnings shows some potential for improvements.

First, there is the step of running an NWP model. Several studies have shown that the use of ensemble prediction systems has benefits compared to pure deterministic forecasts (Buizza and Chessa 2002, Buizza and Hollingsworth 2002, Jung et al. 2005). However, Buizza and Hollingsworth (2002) emphasize that for a forecaster it is necessary to evaluate all ensemble members to find indications for the possibility of the development of an extreme windstorm. In order to facilitate the evaluation of an ensemble forecast, a simplified representation of the ensemble of windstorm forecasts could be provided to the forecaster, analogous to the tracking and clustering method described above. This way information about different possible realizations of forecasted storms, as well as the uncertainty of their temporal and spatial occurrence, could be combined in a single image.

Second, there is the difficulty of choosing certain warning thresholds to adequately issue warnings that are relevant for the local climate of different regions, but also comparable between different regions, e.g. within the European Union. Stepek et al. (2012) show that the use of different, inconsistently chosen warning thresholds in different European countries are currently leading to unrealistically large differences in the issuing frequencies of warnings in neighbouring countries. In order to assist the countries in adapting their thresholds, they suggest a methodology based on pan-European uniform return periods of the annual maximum wind gusts. By adjusting the thresholds with respect to certain return levels of wind gusts, more homogenous warnings could be issued within Europe. Additionally, they note coastal and mountainous regions, which are subject to more extreme wind conditions, have to be treated individually and threshold might have to be adapted to the local conditions.

Third, the step of communicating the warning to the public or to specialized end users related to critical infrastructure offers many possibilities for misinterpretations. Information that is easily understood by an expert can as well be easily interpreted in a wrong way by the public. Broad et al. (2007) show on the basis of hurricane predictions how the issuance of forecast uncertainty is frequently misinterpreted by the public. The US National Hurricane Center (NHC) provides a cyclone track forecast (line) and the so called “Cone of Uncertainty”, which resembles the average forecast error of the track position around the forecasted track (Figure 3.1.7 left). It appears that many people overly focus on the track forecast, assuming that they were save if the line does not cross their area, thus ignoring the uncertainty information given by the cone. Others focused on the boundary of the cone, assuming that they would not be impacted by the storm, if they were outside the boundaries. However, the cone does not tell anything about the severity of the storm, but merely contains information about the uncertainty of the track of the eye. Since 2006 the NHC provides maps with probabilities that certain wind speed thresholds are exceeded (Figure 3.1.7 right). These kinds of figures circumvent problems related to the interpretation of track lines and

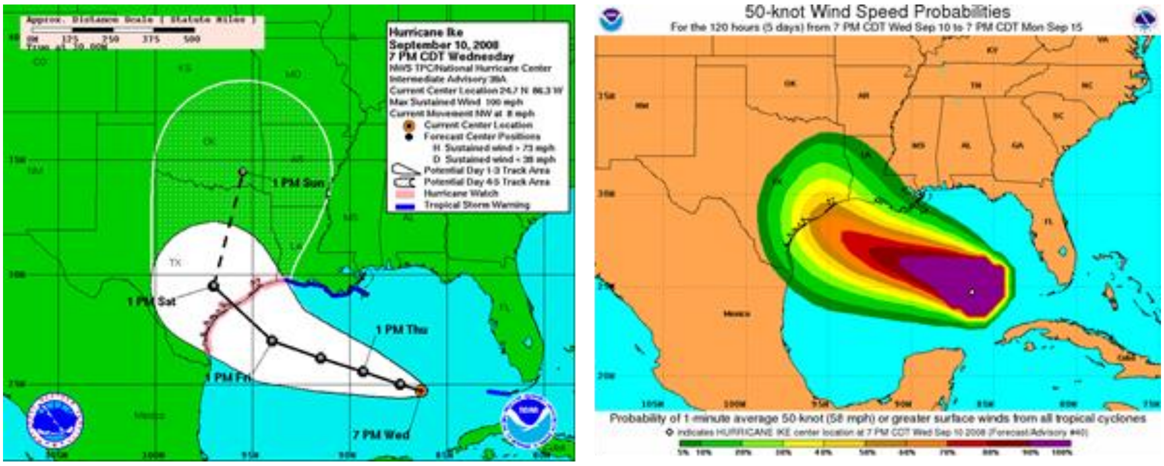

Figure 3.1.7: Forecast of Hurricane Ike. (left) 5-day track forecast, uncertainty cone and (right) 50-knot wind speed probabilities (from http://www.nhc.noaa.gov/archive/2008/IKE_graphics.shtml).

uncertainty cones. The case of the "cone of uncertainty" shows that each individual warning product, which is made available to the public or to other end users, should be tailored to the specific purpose and should be carefully tested regarding its interpretability.

3.1.6 Conclusions

State of the art forecasting systems are able to provide a useful guidance for forecasters to issue warnings of windstorms caused by extra-tropical cyclones. The characteristics of extreme windstorms are captured well within the short range of 0 to 3 days in advance of the event, but indications for the possible occurrence of a windstorm can be achieved even in the medium range of several days. Although there is some skill in seasonal predictions of windstorm activity, it is unrealistic to expect seasonal predictions of windstorms that can be used for warning purposes.

Almost all weather services provide warnings of windstorm events. However the early warning times used by the different weather services vary between 1 and 5 days. It is regarded as problematic that the choice of warning thresholds is not consistent among different member states of the European Union, which leads to large differences in the issuing frequency of storm warnings between neighbouring countries. Furthermore, it is noted that certain warning products are frequently misinterpreted by the public and that such products should therefore be carefully tested before their application.

3.2 Heavy Precipitation

3.2.1 Introduction

Heavy precipitation poses a major threat to critical infrastructure. Land based transportation and emergency services are especially vulnerable to such events. The nature of the events that can be of risk covers a wide range of scales both in space and time. A statistical analysis of extreme rainfall events shows that the intensity (amount per time) decreases with increasing duration, while the accumulated rainfall depth increases with duration. It depends on the individual infrastructure element whether intensity or accumulated depth is more relevant.

Warning systems for extreme precipitation events are in place in most European countries. The first part of this chapter gives an overview about such warning systems. The thresholds for warnings issued by the weather services are compared to the thresholds the infrastructure providers questioned for the RAIN-project regarded as relevant. In addition, the lead times available for warnings of heavy precipitation for different weather services are summarized. The second part of this chapter assesses the ability of current state-of-the-art forecasting systems to predict heavy precipitation. Finally, recommendations to improve the warning systems are given.

3.2.2 Assessment of warning systems

Most European countries have a public warning system for severe weather, which includes heavy precipitation. The warning is usually provided on the internet in the form of a map with a colour code indicating the severity of the danger and symbols indicating the type of event. The individual warnings for 35 different European countries are collected by METEOALARM (www.meteoalarm.eu). These include Austria, Bosnia-Herzegovina, Belgium, Bulgaria, Switzerland, Cyprus, Czech Republic, Germany, Denmark, Estonia, Spain, Finland, France, Greece, Croatia, Hungary, Ireland, Iceland, Italy, Luxemburg, Latvia, Former Yugoslav Republic of Macedonia, Malta, Montenegro, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Sweden, Slovenia, Slovakia and the United Kingdom. METEOALARM uses the following colour scheme:

White: Missing, insufficient, outdated or suspicious data.

Green: No particular awareness of the weather is required.

Yellow: The weather is potentially dangerous. The weather phenomenon that has been forecasted is not unusual, but one should be attentive if one intends to practice activities exposed to meteorological risks and should keep informed about the expected meteorological conditions.

Orange: The weather is dangerous. Unusual meteorological phenomena have been forecasted. Damage and casualties are likely to happen. It is advisable to keep regularly informed about the detailed expected meteorological conditions and should follow any advice given the authorities.

Red: The weather is very dangerous. Exceptionally intense meteorological phenomena have been forecasted. Major damage and accidents are likely, in many cases with threat to life and limb, over a wide area. It is advisable to keep frequently informed about detailed expected meteorological conditions and risks. People should follow orders and any advice given by the authorities under all circumstances and be prepared for extraordinary measures.

The national warning sites usually offer more regional information and further details about the situation than METEOALARM. They can be reached directly or through a link from the METEOALARM site. The thresholds behind the different warning categories (colours) are specified by the national weather services and differ between the countries. Table 3.2.2 gives an overview of these thresholds for heavy precipitation in a number of European countries. It must be noted, that not all countries publish these thresholds on their web site. An analysis conducted for the RAIN project shows that the differences in warning thresholds between the countries are inconsistent and not motivated by climatological differences. When comparing Germany and the Czech Republic, for example, it can be noted that in the Czech Republic higher thresholds need to be reached before a warning is issued (Tab. 3.2.2), even though climatological rain rates are lower (Fig. 3.2.1).

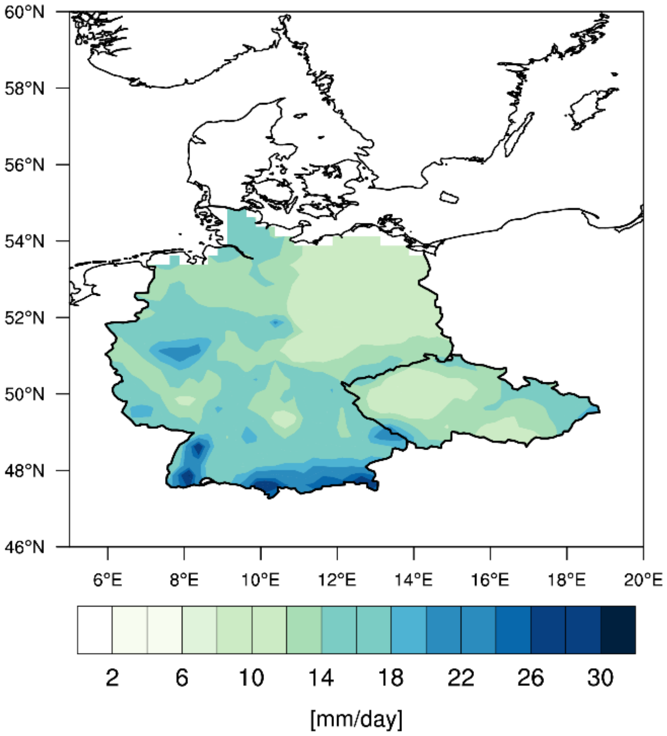

Figure 3.2.1: 98th percentile of daily precipitation in Germany and the Czech Republic in the E-OBS data set for the period 1971-2000.

In many countries free warning and forecast software (apps) for smartphones is available. The German weather service for example offers the warning app (WarnWetter). It is also possible to subscribe to a service that issues warnings via SMS (e.g. the German KatWARN service, which is also free of charge). Warnings are also broadcast on the radio and on television. The weather services also offer customized warnings for infrastructure providers. Warnings to emergency services, state owned railway companies and road administrations are mostly based on non-commercial agreements and free of charge. For the private and commercial sector more detailed information on the expected rain amounts and timing of the events is often only available for paying customers.

For the RAIN project 18 national and commercial European weather services answered to a questionnaire survey. The majority of the interviewed weather services provide warnings about heavy precipitation for land-based transport infrastructure providers, electricity and telecommunication companies, emergency services as well as for the public. Most weather services conduct warnings at fixed thresholds (Table 3.2.3). Depending on the service, 1-4 different warning levels exist. Only 3 out of the 18 questioned services use variable thresholds, which depend on the local climatology. Warning thresholds that depend on the local climatology are higher in areas adapted to high precipitation than in areas which are less often affected by high rain amounts. The number of warnings will then be similar in both regions. When fixed thresholds are used, areas with high climatological precipitation amounts (e.g. in mountainous regions) will on average receive a larger number of warnings than climatologically drier regions.

According to the answers given by the weather services most services issue warnings for events with a high overall rain amount accumulated over several hours (between 6 and 24 hours depending on the weather service). Only 2 weather services stated that they issue warnings for high intensity convective events of short duration (hourly or sub-hourly values). This is in contrast to the needs expressed by the stakeholders that have been interviewed. About half of them stated that the critical infrastructure can be affected by high intensity events of short duration.

Table 3.2.1: Critical thresholds for heavy precipitation given by interviewed infrastructure operators and emergency services

Type of Infrastructure / Operator	Threshold
Telecom	1 mm/h small impact 20 mm/h high impact
Rail	>100 mm/h
Rail	100 mm/24h in alpine area, 60 mm/24h in flat terrain if rainy pre-history (>100 mm/3day before), then 50 mm/24h already relevant
Road	75-100 mm/24h
Road	5 mm/h (risk for aquaplan), 50 mm/24h (flooding, risk for collapse of road banks)
Emergency Service	20 - 30 mm/h, 70 -120 mm/24h
Emergency Service	20 mm/h
Emergency Service	20 mm/h
Emergency Service	>30 mm/h
Emergency service	25 mm/h, 35 mm/6h
Emergency service	100 mm/24h

country	mm/ h	mm/ 3h	mm/ 6h	mm/ 12h	mm/ 24h	mm/ 48h	mm/ h	mm/ 3h	mm/ 6h	mm/ 12h	mm/ 24h	mm/ 48h	mm/ 72h	mm/ h	mm/ 3h	mm/ 6h	mm/ 12h	mm/ 24h	mm/ 48h	mm/ 72h
Bulgaria			30		15						35							65		
Switzerland					30						50	80	100					80	110	130
Cyprus		45	50		55			65	70		85				90	95		115		
Czech Republic			30	35	40					50	60					50	70	90	120	
Germany	15		20	25	30	40	25		35	40	50	60		40		60	70	80	90	
Denmark			24																	
Estonia				15						50										
Finland	20				50		30				70			45				120		
Croatia			15		25				45		60					80		95		
Hungary		25			20			50			30							50		
Ireland			20	25	30				30	40	50					40	50	70		
Italy			10		20				30		50					50		100		
Luxembourg		10	15		30			20		30	45				35	45		60		
Malta					30						60							75		
Netherlands	30										75									
Norway		25						35							50					
Portugal	10-20		30-40				21-40		41-60					40		60				
Rumania					25						50							90		
Serbia		10		20	30			20		30	40				30		40	60		
Sweden				35							70									
Slovakia			35	45	55				55	70	90									
Slovenia			15		20				25		40					60		80		

Table 3.2.2: Warning thresholds used in METEOALARM for precipitation

Table 3.2.3: Warning thresholds for heavy precipitation, answers from RAIN questionnaire.

	Warning Thresholds		
Weather Service	Low	Medium	High
UBIMET GmbH	30 mm/24h	50 mm/24h	100 mm/24h
SMHI - Swedish Meteorological and Hydrological Institute	>35 mm/12h		>70 mm/24h
Latvian Environment, Geology and Meteorology Centre			
MeteoNews AG	depending on surrounding weather conditions		
MeteoLux / Administration de la navigation aérienne	3.3 – 6.3 mm/h	6.4 – 11.6 mm/h	> 11.6 mm/h
Icelandic Meteorological Office	30 mm/12h		
ZHMS of Montenegro	100 mm/24h		
Lithuanian Hydrometeorological Service	15-49 mm/12h	≥50-80mm/12h	>80 mm/12h
Czech Hydrometeorological Institute	> 30 mm/6h or 35 mm/12h or 40 mm/24h;	> 50 mm/12 h or 60 mm/24 h;	> 50 mm/6h or 70 mm/12h or 90 mm/24h or 120 mm/48h
MeteoNetwork ONLUS	No warnings issued		
Slovak Hydrometeorological Institute	25 mm/6h or 30 mm/12h or 35 mm/24h	35 mm/6h or 45 mm/12h or 55 mm/24h	55 mm/6h or 70 mm/12h or 90 mm/24h
Danish Meteorological Institute	>15 mm/30min or > 24 mm/6h total > 50 mm		
ZAMG	depending on partner organization, mostly climatological frequencies		
BLUE SKY Wetteranalysen	30mm/24h		
Geo-Meteo	>30 mm/24h		
Norwegian Met. Institute	Depends on regional climatology		

Table 3.2.4: Availability of issued warning products

Availability of warning products (issued products)	Heavy precipitation						
Forecasting ranges according to WMO	0 – 2 h, Now-casting	2 – 12 h, Very Short Range Fore-casting	12 – 72 h, Short Range Fore-casting	72 – 240 h, Medium Range Forecasting	10 – 30 d, Extended Range Fore-casting	1 – 3 m, 3 Month Outlook, Long Range Fore-casting	3 m – 2 y, Seasonal Outlook (departure from climate values)
Public warning products at a given schedule	+	+	+	o	-	-	-
Public warning products and updates issued at any time necessary (24 h continuous monitoring)	+	+	+	?	-	-	-
Tailored warning products for CI customers at a given schedule	+	+	+	o	-	-	-
Tailored warning products and updates for CI customers issued at any time necessary (24 h continuous monitoring)	+	+	+	?	-	-	-
Communication with CI customers on a case by case basis (no fixed agreement)	+	+	+	o	-	-	-
Routine general forecasts (no products for extreme weather events)	+	+	+	+	o	o	o

Source of WMO definitions: "DEFINITIONS OF METEOROLOGICAL FORECASTING RANGES", retrieved on 30 March 2015: http://www.wmo.int/pages/prog/www/DPS/GDPS-Supplement5-AppI-4.html Availability categories:

-	Not available.
o	Available from some weather services in Europe.
+	Available from many weather services in Europe (standard product).
?	Unknown.

3.2.3 Predictability

Verification methods for (heavy) precipitation

As pointed out by Rodwell et al. (2010) precipitation is a difficult quantity to verify because it is rather sparsely observed by surface observations and imperfectly estimated by radar and satellite. In addition, a point observation may not be representative of a model grid-box average. Further, precipitation has a heterogeneous spatio-temporal distribution, often with a large number of dry days and occasional extreme events.

The skill of a prediction is usually judged with the help of scores. A precipitation score must contend with the issues mentioned above. As a result, many different scores are in use for precipitation verification. They can be divided into categorical (dichotomous and multi-category) and continous scores. In addition, spatial or object oriented methods exist.

Categorical scores: Often categorical scores use two classes. In case of precipitation one would differentiate between dry days and rainy days. An example for a dichotomous score is the 'Hit-Rate' or 'Probability of Detection' score defined as H/(H+M) where H is the number of correctly forecast events (hits) and M is the number of observed events that were not predicted (misses). For a perfect forecasting system, Hit-Rate=1. However, the converse is not true. A trivial forecast that always predicted the event would have Hit-Rate=1 but is clearly not a perfect forecasting system. The Peirce skill score is the Hit-Rate minus the False-Alarm-Rate. Unlike the Hit-Rate alone, the Peirce skill score does include a penalty for false alarms and is less easily increased by overpredicting the event.

For a categorical score that assesses both the prediction of dry weather and precipitation quantity, more than two categories are required. A simple n-category score is the Heidke skill score. This score rewards a hit in any category equally and penalizes all misses equally, regardless of the class of category error.

ECMWF developed a new verification score, SEEPS (Stable Equitable Error in Probability Space) to monitor the long-term trend in performance for forecasting precipitation (Haiden et al. 2012). The score used three categories: "dry", "light precipitation" and "heavy precipitation". The boundary between "light" and "heavy" is determined by the station climatology so that SEEPS assesses salient features of the local weather and accounts for climate differences between stations. The SEEPS varies between 0 and 1, with 1 being a perfect forecast and 0 being a forecast with no skill.

Continuous scores: Some continuous scores of precipitation have been tested. Rodwell (2005) for example analyses the spatial correlation of normalized precipitation. However, the contributions to the score from different regions within the area of interest are difficult to assess. In addition, the correlation is sensitive to extreme values, whether real or due to erroneous observations, and this increases the score's uncertainty. Ward and Folland (1991) applied the LEPS (Linear error in probability space) approach to continuous (as well as categorical) seasonal-mean precipitation anomalies. The error is estimated in probability space as opposed to measurement space, which ensures that the correct forecast of an extreme event has more weight than the correct forecast of a moderate event.

Object oriented methods: An example for an object oriented verification method is the contiguous rain areas (CRA) method developed by Ebert and McBride (2000). It aims at answering the question what the location error of a spatial forecast is, and how this total error breaks down into components due to incorrect location, volume, and fine scale structure. CRA verification uses pattern matching techniques to determine the location error, as well as errors in area, mean and maximum intensity, and spatial pattern. The total error can be decomposed into components due to location, volume, and pattern error.

Rare events: The value of most scores is dominated by the contribution of the events that occur most frequently. In order to assess the skill of a forecast with respect to rare events, measures are needed that give more weight to such events. Examples are the (symmetric) extreme dependency score (S)EDS and the (symmetric) extremal dependence index (S)EDI, which range between -1 and 1, where 0 indicates no skill. The SEDS and EDS both have some weaknesses, as they depend on the rate at which extreme events occur. Before the calculation of the scores, Ferro and Stephenson (2011) recommend the recalibration of the forecast.

Hewson (2007) proposed the deterministic limit for categorical forecasts of a pre-defined rare meteorological event. It is the forecast lead time at which the warning becomes meaningless because the number of misses plus false alarms equals the number of hits.

A good summary of the numerous verification methods in use can be found here: http://www.cawcr.gov.au/projects/verification/

Precipitation forecasts and their skill

The following section summarizes the methods used to conduct precipitation forecasts of various lead times. Information about their skill according to the recent scientific literature is given. The statements about the availability of warnings for the different forecast lead times are based on the weather service interviews. The results are summarized in Table 3.2.5.

Nowcasting: Short-term forecast over a few minutes up to two hours are also known as nowcasts. To forecast heavy precipitation convective cells are mapped. An estimate of their speed and direction of movement is used to forecast the situation a short period ahead, assuming the systems will move without significant changes. The convective cells are identified and tracked using radar measurements. Some nowcasting routines also take dynamic weather forecasts into account.

In 2013 an initiative to improve the nowcasting methods within the EUMETNET community finished. The project was called INCA-CE (Integrated Nowcasting through Comprehensive Analysis – Central Europe; website: http://www.inca-ce.eu/) and aimed at implementing a transnational weather information system. 23 national weather services were involved (Kann et al. 2012).

Short-range to medium-range forecasting: Short and medium-range forecasts are usually based on ensembles of Numerical Weather Prediction (NWP) simulations. At ECMWF, for example, 52 individual ensemble members are created twice a day. Initial state and model physics slightly differ between the ensemble members. The analysis of the ensemble spread helps to explore the range of uncertainty in the observations and the model. In addition to global models some weather services run regional models to further refine the resolution of the forecast. The boundary conditions for the regional models are provided by the global models. The German weather service for example routinely runs the regional models COSMO-EU and COSMO-DE. Both are started every 3 hours. They run for 78 hours/27 hours respectively.

To help the NWP centres to improve their forecasts and to guide operational forecasters it is useful to compare and verify predictions produced by different centres. The World Meteorological Organization (WMO) issued recommendations for the verification and intercomparison of the forecasts. Based on these recommendations ECMWF regularly evaluates forecast precipitation from a number of European forecast models against observed precipitation amounts reported from SYNOP (a WMO numerical code for synoptic surface weather observations) stations. The results are available from their web site (http://apps.ecmwf.int/wmolcdnv/). Figure 3.2.1 shows the evolution of the SEEPS skill score for precipitation with increasing forecast lead time for 4 global NWP models. The curves indicate that the skill of the models to forecast precipitation over Europe converges to zero after 8 to 10 days.

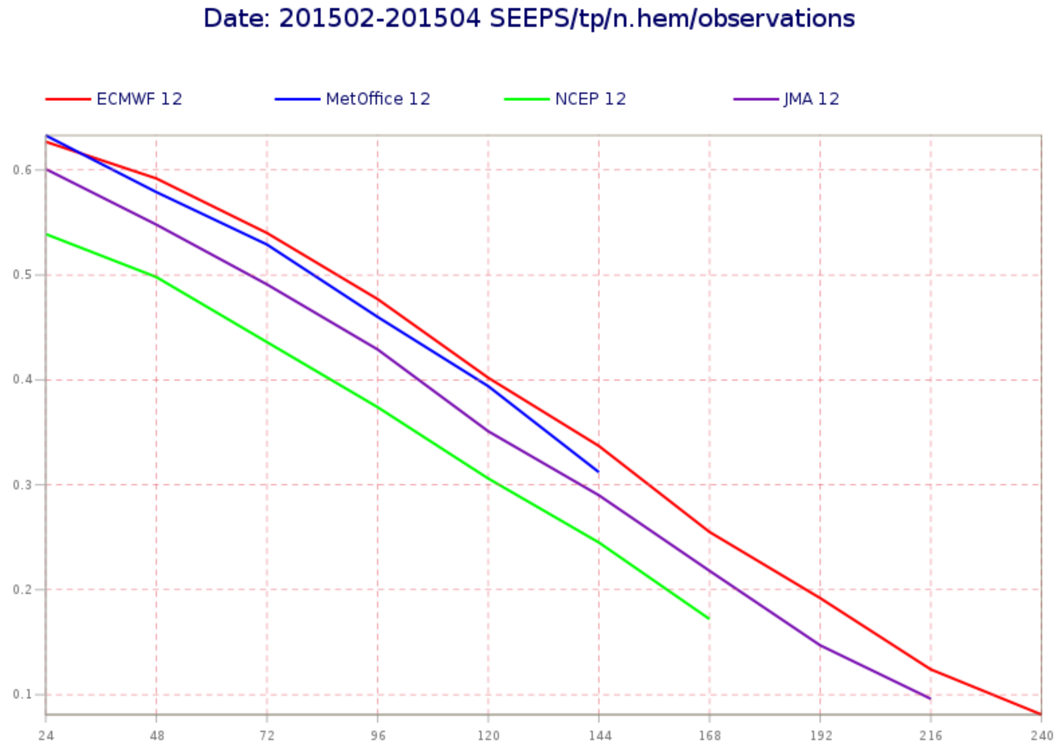

Figure 3.2.2: SEEPS skill score depending on forecast lead time in hours for 4 NWP models. Mean over Europe for the period February-April 2015.

Extended-range forecasting: Monthly (sub-seasonal) forecasts are routinely produced at ECMWF since 2002. They are currently started twice a week and run for 32 days. Re-forecasts are conducted with a 5-member ensemble. An analysis of skill scores for the ECMWF sub-seasonal forecast was published by Vitart (2014). He found that precipitation skill scores over the Northern Extratropics are low compared to the 2m-temperature scores. The forecasts have improved in previous years and the sub-seasonal forecast is now potentially useful 25 days into the future. It is, however, not possible to forecasts the time and location of heavy precipitation events. No warnings are issued at these time ranges.

Seasonal forecasting: Seasonal climate prediction is nowadays a well-established operational area and different centres around the world run global seasonal forecasting systems. The EUROSIP multi-model seasonal forecasting system (Palmer et al., 2004; Vitart et al., 2007) was developed for Europe. It consists of a number of independent coupled seasonal forecasting systems integrated into a common framework. From September 2012, the systems include those from ECMWF, the UK Met Office, Météo-France and NCEP (United States National Centers for Environmental Prediction). The best skill of these forecasts is related to the El Niño – Southern Oscillation (ENSO) and found in the tropics (e.g. Kim et al. 2012).

A recent paper of Weisheimer and Palmer (2014) analyses the reliability of seasonal climate forecasts of the ECMWF seasonal forecast system. They rank the seasonal forecasts on a scale of 1–5 and find a wide range of 'goodness' rankings, depending on region and variable. The self-defined ranking categories used in the study are "perfect", "still useful", "marginally useful", "not useful" and "dangerous to use". The forecasts of rainfall over Europe are currently only ranking between marginally useful, not useful and dangerous to use (Fig.3.2.2).

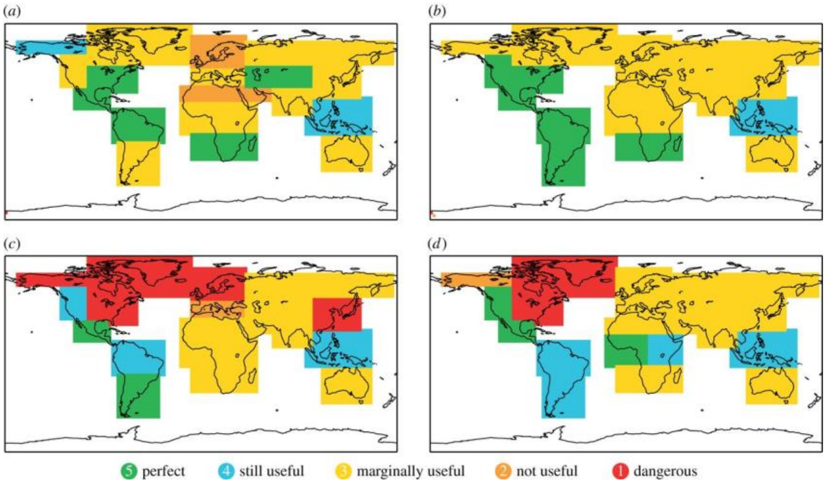

Fig. 3.2.3: Reliability of System 4 seasonal forecasts for precipitation. (a) Dry December-January-February (DJF), (b) wet DJF, (c) dry June-July-August (JJA) and (d) wet JJA. From Weisheimer and Palmer (2014)

Table 3.2.5: Skill of products for different lead times and CI sectors.

Typical **Skill** of warning products (issued products)	Heavy precipitation						
Forecasting ranges according to WMO	0 – 2 h, Now-casting	2 – 12 h, Very Short Range Fore-casting	12 – 72 h, Short Range Fore-casting	72 – 240 h, Medium Range Forecasting	10 – 30 d, Extended Range Fore-casting	1 – 3 m, 3 Month Outlook, Long Range Fore-casting	3 m – 2 y, Seasonal Outlook (departure from climate values)
Public warning products	+	+	+	o	-	-	-
Tailored warning products and updates for CI customers from land transport sector	+	+	+	o	-	-	-
Tailored warning products and updates for CI customers from energy sector	+	+	+	o	-	-	-
Tailored warning products and updates for CI customers from tele-communication sector	+	+	+	o	-	-	-

Skill categories:

-	Products not available or useless.
o	Little use for some applications.
+	Useful, strong additional value compared to mean climate information.
?	Unknown.

3.2.4 Findings from additionally retrievable examples of warning products

In addition to the public warning systems, specialized products are available for specific sectors. In Germany such a specialized product is the Firefighter Information System (FEWIS), which is a web-based tool for emergency services. To prevent an overload of the internet server during critical situations, the system is restricted to professional users. All users are trained to use FEWIS before getting access. An important component of FEWIS is WebKONRAD, which shows the current situation and provides short-term forecasts (nowcasts) for heavy precipitation. WebKONRAD maps convective cells and then uses an estimate of its speed and direction of movement to forecast the situation a short period ahead — assuming the systems will move without significant changes. The convective cells are identified and tracked using radar measurements.

Rather than issuing warnings over large regions, UBIMET offers user tailored weather warnings to infrastructure operators and emergency services that take the exact location of critical infrastructure elements (e.g. railway tracks, mountain passes) into account.

A similar approach is adopted for Germany’s Road Condition and Weather Information System (Straßenzustands- und Wetterinformationssystem, SWIS). Forecasts and warnings can be issued for specific roads. Sensors next to the roads measure the conditions (e.g. precipitation, slipperiness) every 15 minutes. The information is combined with weather station and radar measurements. The service is available for paying customers. It is for example also used to alert the winter services if necessary.

On a commercial basis the UKMet Office also offers products which take the exact location of the elements into account to private infrastructure providers for example to railway companies (e.g. http://www.metoffice.gov.uk/railways/openrail).

3.2.5 Recommendations to improve the warning system

Weather services and stakeholders both wish for an improvement of forecast accuracy for precipitation (especially convective systems) in terms of timing, location and precipitation amount. Some weather services state that they would benefit from an improvement of EU internal data exchange and cooperation. Currently there is the conception that some national services hinder European developments because they fear negative influences on their business. Several weather services state that more common codes to compare and exchange data, forecasts and warnings may help to improve this situation. The problem of data availability is even more pronounced for private weather services, which often have problems to obtain even national data. The data mostly has to be paid for. A private weather company even expressed its fear that private weather companies won’t benefit from results obtained by European projects.

In some countries lack of money and technical equipment limits the quality of weather warnings. Here the installation of additional meteorological/hydrological stations and a radar network would improve detection of severe precipitation and warnings.

Some weather services see room for improvement of user tailored and user friendly warning systems. Such a system could for example include the option for stakeholders to customize the thresholds for warnings. This could be useful as stakeholder interviews have shown that different types of infrastructure elements are vulnerable to different types of events and different thresholds (short duration with high intensity or long duration with high accumulated precipitation depth). In addition, the communication between weather services and stakeholders may be improved. For example severity and expected impact may be specified in more detail. Another aspect is the problem to find a balance between “staying on the save side” and “over-warning”. It is a well-known problem that after a high number of false alarms people tend to take warnings less serious. This could be overcome by probabilistic forecasts. Those however need to be communicated in a way that enables the users to interpret them correctly. In this context one of the questioned weather services mentioned the need to conduct further research on probabilistic forecasts.

The author's personal suggestion is to establish a routine that validates each warning after the end of the warning period and to place the results on the web site. The site could be used to inform the users after each successful/unnecessary warning which aspects of the situation were judged correctly or why the situation developed in an unexpected way. This may help to increase the trust in the warnings and to improve the understanding of interested stakeholders in the uncertainties and limitations of the weather forecasts. It would also force weather services to reflect their warning policy.

3.2.6 Conclusions

First warnings about heavy precipitation events are issued 2-5 days prior to the event. The skill of numerical weather models to forecast precipitation in Europe (not extremes) becomes marginal after 10 day of forecast lead time. Beyond this time frame it is attempted to predict at least deviations from the mean state, which so far has not been very successful for precipitation over Europe. An important tool to monitor and predict the situation of heavy precipitation situations close to the event is nowcasting, which is mainly based on radar observation. Some countries lack an adequate radar detection network and would benefit from the installation of such a network. Public warnings are, however, available for most European countries. In addition some weather services have developed customized warning tools for infrastructure providers. There is however potential for further developments. The questionnaires indicate that there may be a mismatch of warning products provided by the weather services and the needs of infrastructure providers. Warnings issued by the weather services focus on events with high rainfall amounts, while infrastructure providers are sometimes more concerned about events with high rainfall intensity.

3.3 Coastal floods

3.3.1 Introduction

Early warning systems for coastal floods are not common in Europe. Modelling those events is complex; they are also relatively rare compared to other meteorological hazards. A third of interviewed weather services provide them, while only a quarter of interviewed stakeholders use them. Warning thresholds are locally defined, as the coast varies substantially between places.

3.3.2 Assessment of warning systems

Description of warning systems

Early warning against coastal floods is done by detecting the occurrence of dangerously high sea levels caused by storms. Creating such predictions requires a hydrodynamic model of the sea; the size of the model is defined by the characteristics of the basin. The models are forced by forecasted wind speeds and directions together with air pressure. For most of European coasts, a model of tides needs to be added in order to obtain correct water levels. In Figure 3.3.8 results of a sea level forecast from the Danish Meteorological Institute are presented. This 2-day prediction was made using hydrodynamic bead modeling (HBM) forced by DMI-Hirlam high resolution meteorological model (DMI 2015). If the water level is forecasted to exceed 125–240 cm above mean sea level (depending on location) a warning is issued for an appropriate section of the coast (Figure 3.3.9).

An extension of coastal early warning systems, operational insofar only at local scale, involves integrating sea level forecast with wave models and morphodynamic models of the coast. An example warning system, operational on a section of the Polish Baltic Sea coast, is seen in Figure 3.3.10. This one of nine test sites developed during EU-funded Micore project (Ferreira et al. 2009). If medium or high level of dune overwash is indicated, risk of flooding occurs, as the water may breach those natural flood defences in that situation.

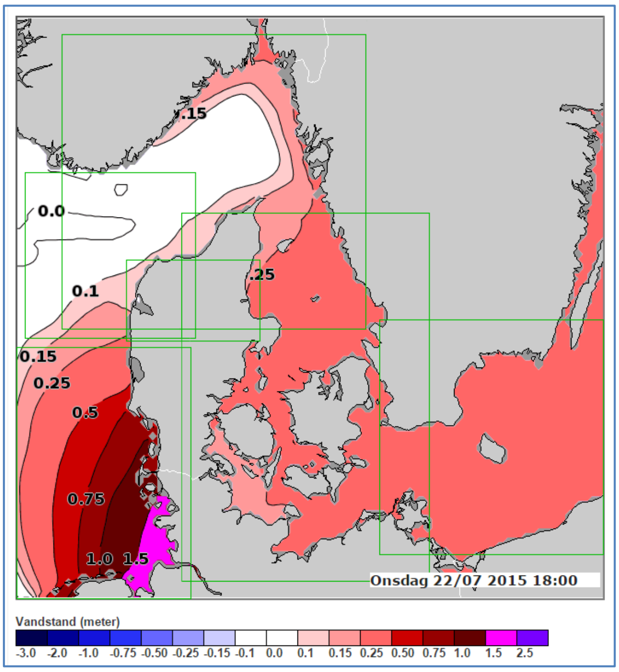

Figure 3.3.8. Sea level forecast in waters surrounding Denmark in meters, July 2015 (DMI 2015).

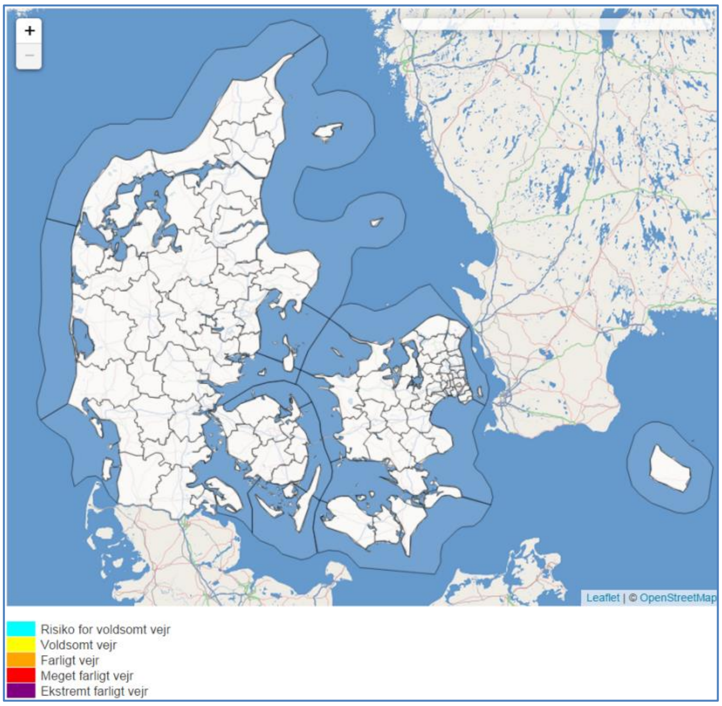

Figure 3.3.9. Warning zones in Denmark, including numerous coastal sections and five degrees of hazard (DMI 2015).

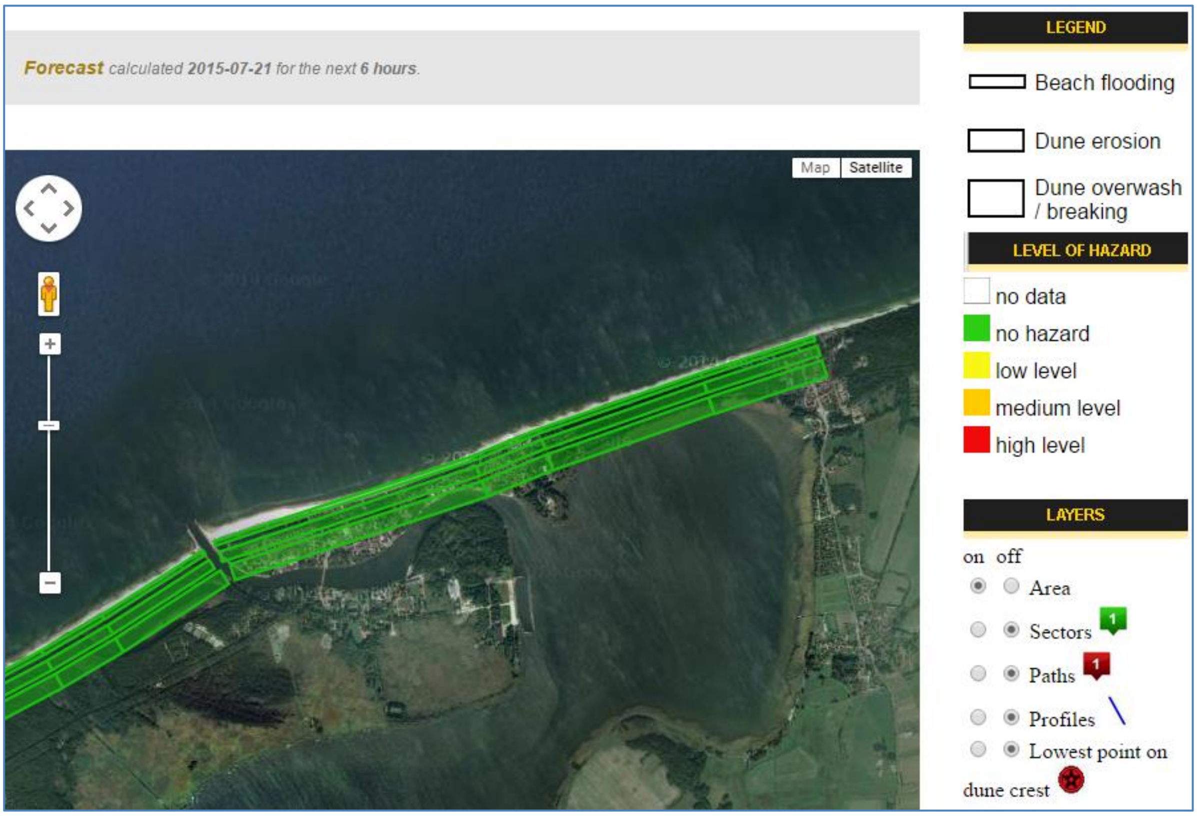
Forecast calculated **2015-07-21** for the next **6** *hours*.

Figure 3.3.10. Pilot early warning system for Dziwnów, Poland, which integrates sea level and wave parameters with morphodynamics of the coast (INoM US 2015).

There is no dedicated pan-European coastal flood warning system, though "coastal events" are included on Meteoalarm website. 16 out of 26 Meteoalarm participant countries with sea access provide such information[1], mostly being warnings for rough sea conditions related with high waves and strong winds. Some countries which do not supply coastal warnings to Meteoalarm perform sea level modelling (United Kingdom, Iceland), while other limit activities to issuing warnings for shipping (Italy, Greece).

Summary of the interviews

A total of 6 weather services out of 18 interviewed weather services provide warnings for coastal floods. The interviewed institutions included 3 national weather services from landlocked countries. Only one out of 4 commercial weather services issues warnings and only on irregular basis. Two weather services provide scheduled forecasts, while 3 issue them when necessary. In 4 cases out of 5 (where information on forecast ranges was given), the range of the forecast is only short-term (less than 3 days), and in the remaining case is medium-term. All of the warnings are manually issued by a meteorologist; none of the interviewees mentioned tailored warnings for infrastructure operators.

From the user side, 17 out of 29 interviewed infrastructure operators consider coastal floods as a hazard to their assets or operations (4 of them were from landlocked countries). However, only 5 of them use coastal flood forecasts (10 operators did not use forecasts at all or didn't answer to the question). Range of forecast mentioned by the operators is somewhat longer than found in weather services' interviews, with 4 out 5 users utilizing medium-term forecasts.

Warning thresholds

The threat posed by storm surges depends mainly on local topography, therefore warning thresholds are also defined locally. In the questionnaires, only two meteorological services mentioned their thresholds. Swedish Meteorological and Hydrological Institute releases level 1 (lowest) warning if sea level is predicted to increase more than 60–80 cm above average depending on location. For level 2 (medium), the threshold is 100–120 cm depending on location. At German Weather Service, the threshold sea level is 85–125 cm above average.

Polish Institute of Meteorology and Water Management defines thresholds separately for each tide gauge along the coast. Table 3.3.4 collects thresholds for all coastal stations with an example visualisation in Figure 3.3.11. The thresholds are defined based on local flood protection requirements. Warning levels occur in most locations almost every year, while alarm levels correspond to various return periods. Meanwhile, the Finnish Meteorological Institute uses probability of occurrence as a definition of thresholds. Sea level is considered dangerous if it constitutes a 5-year event and very dangerous if it's a 20-year event (Table 3.3.5). However, this corresponds to different sea levels at various sections of the coast.

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[1] Belgium, Denmark, Estonia, Finland, France, Ireland, Latvia, Montenegro, Malta, Netherlands, Norway, Poland, Portugal, Slovenia, Spain, Sweden.

Table 3.3.4. Warning and alarm levels at selected stations along the Polish coast. Values are in cm above reference level (mean sea level is about 500 cm). Source: adapted from IMGW (2015).

Stations	Warning level	Alarm level
Trzebież	540	560
Władysławowo, Hel, Puck, Gdynia, Gdańsk Port Północny, Gdańsk Sobieszewo	550	570
Wolin, Świnoujście, Dziwnów	560	580
Ustka	570	600
Kołobrzeg, Darłowo, Łeba	570	610
Nowa Pasłęka, Tolkmicko	590	630
Gdańsk Ujście Wisły, Gdańsk Świbno	600	680

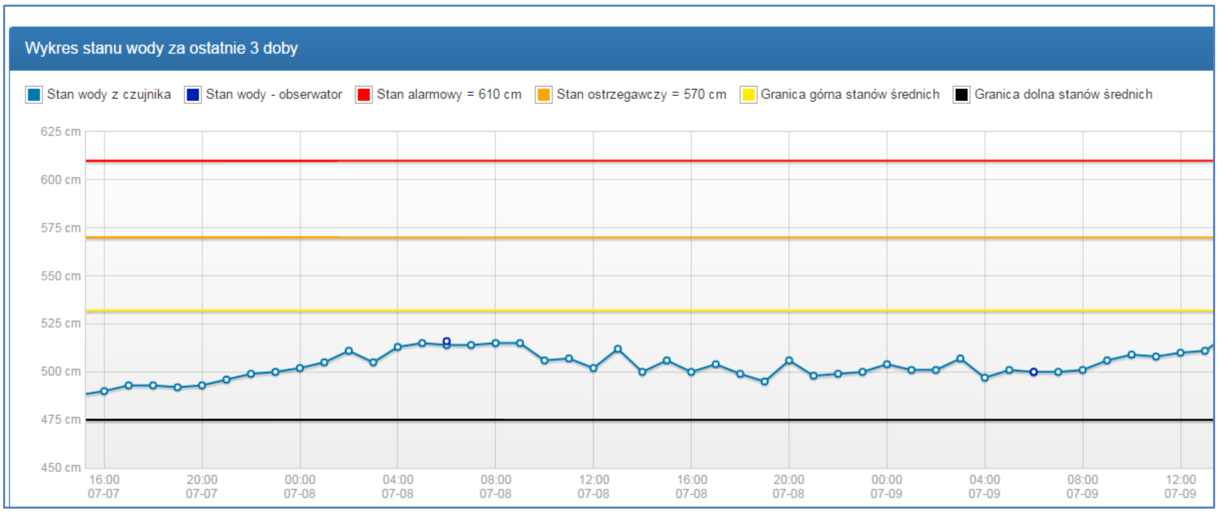

Figure 3.3.11. 3-day sea level at tide gauge in Kolobrzeg, Poland. Blue line is the observed water level, whereas orange line is the 'warning level' (defined at this station at ca. 70 cm above mean sea level) and red line is the 'alarm level' (around 110 cm) (IMGW 2015).

Table 3.3.5. Warning thresholds for extreme sea level in Finland. Source: adapted from Finnish Meteorological Institute (2015).

Warning level	**High water**	**Very high water**	**Dangerously high water**
Frequency of occurrence	once a year	once in 5 years	once in 20 years
Region	**Water level (cm above mean)**		
Northern Bay of Bothnia	115	140	170
Southern Bay of Bothnia	85	110	130
The Quark and Sea of Bothnia	75	100	120
Sea of Åland and Archipelago (Föglö)	65	85	100
Sea of Archipelago (Turku), Western Gulf of Finland (Hanko)	70	95	110
Western Gulf of Finland (Helsinki)	80	115	130
Eastern Gulf of Finland	110	145	175

Availability of products

The availability of products and lead times, based on interviews and information on providers' websites is summarized in Table 3.3.6. It can be noted that products are limited to short and medium range forecasting, available in some countries. Virtually all countries with access to the sea issue warnings for storm conditions on the sea, but not all of them give specific warnings for the coastal zone in terms of potential flooding.

Table 3.3.6. Availability of warning products for coastal floods.

Availability of warning products (issued products)	Coastal floods						
Forecasting ranges according to WMO	0 – 2 h, Now-casting	2 – 12 h, Very Short Range Fore-casting	12 – 72 h, Short Range Fore-casting	72 – 240 h, Medium Range Forecasting	10 – 30 d, Extended Range Fore-casting	1 – 3 m, 3 Month Outlook, Long Range Fore-casting	3 m – 2 y, Seasonal Outlook (departure from climate values)
Public warning products at a given schedule	-	-	o	o	-	-	-
Public warning products and updates issued at any time necessary (24 h continuous monitoring)	-	-	o	o	-	-	-
Tailored warning products for CI customers at a given schedule	-	-	o	o	-	-	-
Tailored warning products and updates for CI customers issued at any time necessary (24 h continuous monitoring)	-	-	-	o	-	-	-
Communication with CI customers on a case by case basis (no fixed agreement)	-	-	o	-	-	-	-
Routine general forecasts (no products for extreme weather events)	-	-	+	o	-	-	-

Source of WMO definitions: “DEFINITIONS OF METEOROLOGICAL FORECASTING RANGES”, retrieved on 30 March 2015: http://www.wmo.int/pages/prog/www/DPS/GDPS-Supplement5-AppI-4.html

Availability categories:

-	Not available.
o	Available from some weather services in Europe.
+	Available from many weather services in Europe (standard product).
?	Unknown.

3.3.3 Predictability

Forecasting of sea water levels started in the 1980s and these warnings were constantly improved, providing now relatively accurate warnings (Alfieri et al. 2012, Verlaan et al. 2005). In recent years, introduction of ensemble forecasts (Flowerdew et al. 2010) and improvement of tidal models (Zijl et al. 2013) led to further reduction of errors in predictions of sea levels. However, quality of forecasts varies between stations. An example from the Dutch warning system (Figure 3.3.12) shows that for most stations root mean square error (RMSE) is around 10–20 cm for a 6-hour forecast (Verlaan et al. 2005). Also Danish Meteorological Institute's model has absolute relative peak error[2] ranging from 5% to 45% depending on location (Figure 3.3.13). The highest errors were recorded at stations located in the Danish Straits, where properly modelling those narrow passages proved difficult (Kliem et al. 2006).

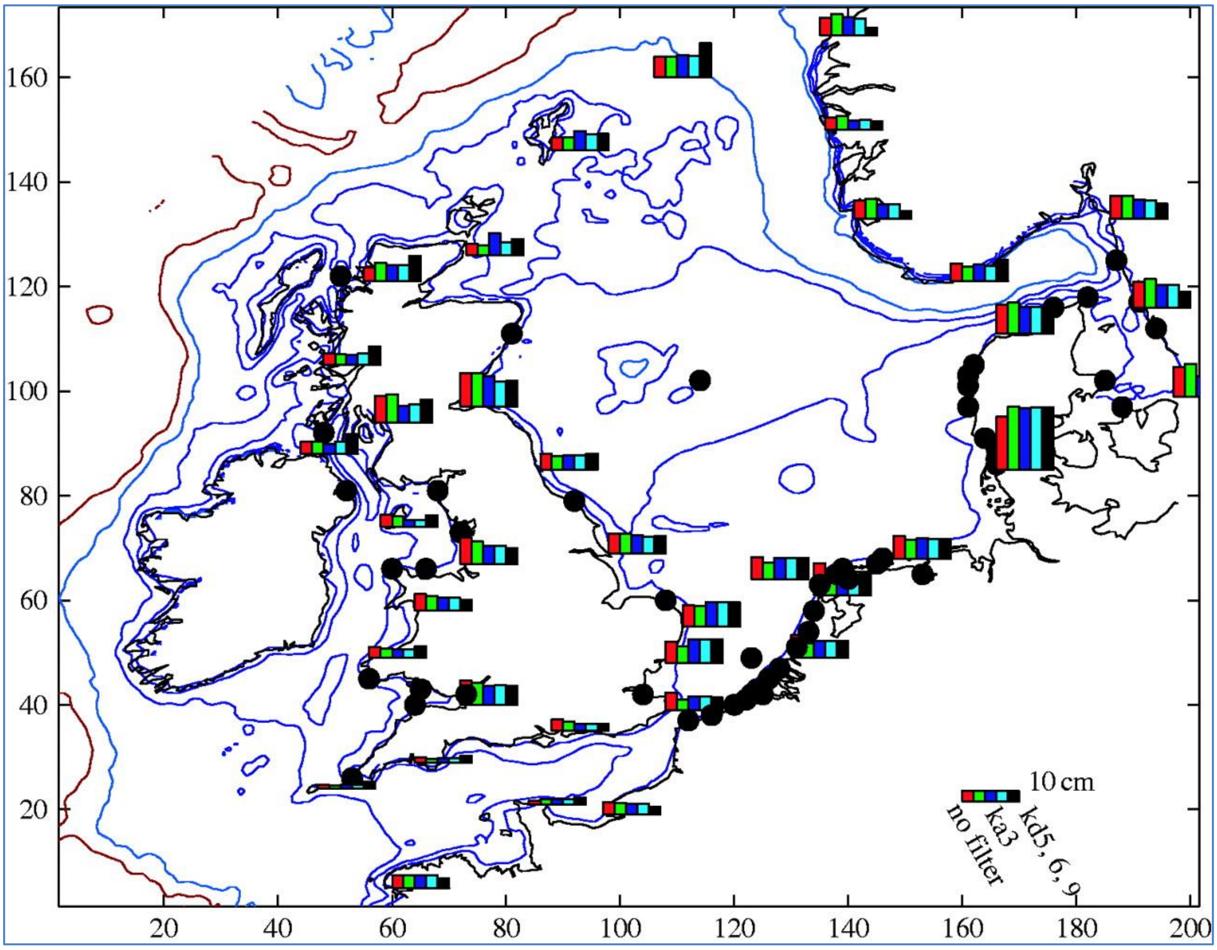

Figure 3.3.12. Root mean square error (in centimetres) of a 6-hour forecast of water levels at selected measurement stations during a storm on 4 December 1999 (Verlaan et al. 2005). Different colours of the bars represent different data assimilation methods.

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[2] This indicator is the difference between the maximum water level which could be found in the observational data, and the maximum water level in the output of the simulation, divided by the maximum water level from the observations.

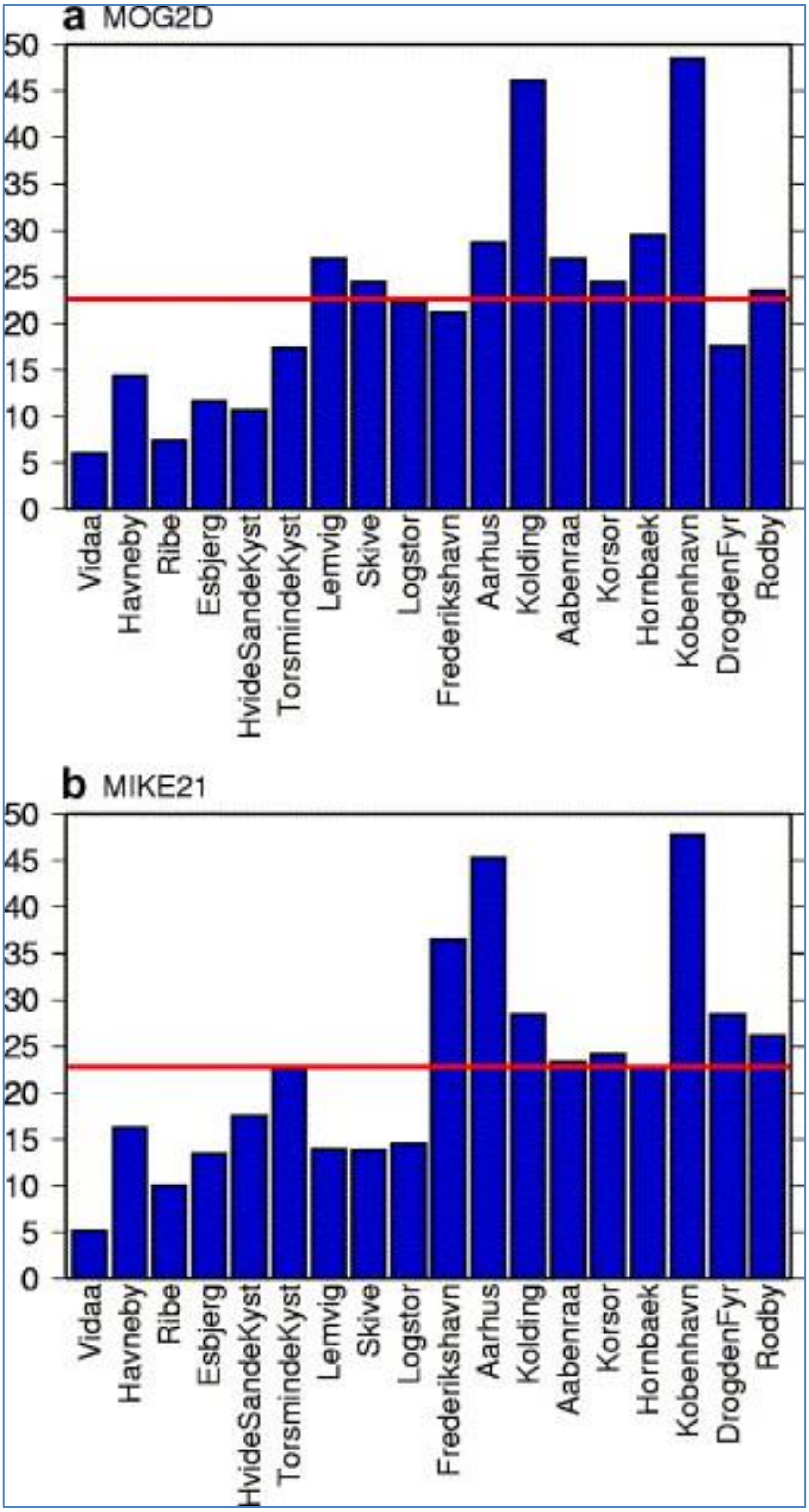


Figure 3.3.13. Absolute relative peak error (%) for Danish tide gauges from two forecasting models (Kliem et al. 2006).

Table 3.3.7. Skill of coastal flood warnings.

Typical **Skill** of warning products (issued products)	Coastal floods						
Forecasting ranges according to WMO	0 – 2 h, Now-casting	2 – 12 h, Very Short Range Fore-casting	12 – 72 h, Short Range Fore-casting	72 – 240 h, Medium Range Forecasting	10 – 30 d, Extended Range Fore-casting	1 – 3 m, 3 Month Outlook, Long Range Fore-casting	3 m – 2 y, Seasonal Outlook (departure from climate values)
Public warning products	-	-	+	+	-	-	-
Tailored warning products and updates for CI customers from land transport sector	-	-	o	o	-	-	-
Tailored warning products and updates for CI customers from energy sector	-	-	-	o	-	-	-
Tailored warning products and updates for CI customers from tele-communication sector	-	-	o	-	-	-	-

Skill categories:

-	Products not available or useless.
o	Little use for some applications.
+	Useful, strong additional value compared to mean climate information.
?	Unknown.

3.3.4 Recommendations to improve the warning system

We see a potential for improvements in:

- Extending the range of warnings by introducing nowcasting and long-range forecast systems.
- Increasing the resolution of the models, as well as improving tidal models.
- Expanding warning based not only on sea levels, but also on the morphological factors in the coast (erosion and dune breach).
- Publishing more information on the validation of warnings.
- Creating a pan-European warning system similar to one existing for river floods.

3.3.5 Conclusions

To conclude, the availability, range and dissemination of coastal flood warnings in Europe is modest compared to river floods and other meteorological hazards. Coastal floods are relatively rare and do not concern all countries, however they usually affect several of them at once, creating a need for a pan-European system.

3.4 River floods

3.4.1 Introduction

Early warning systems for river floods are common and essential in Europe. Modelling those events is relatively complex, but necessary as high river discharges often occur. More than half of interviewed weather services provide them, while a bit more than a third of interviewed stakeholders use them. Warning thresholds are locally defined, because river discharges pose different threats depending on the size of the river and various local conditions.

3.4.2 Assessment of warning systems

Description of warning systems

Early warning against river floods is done by detecting the occurrence of dangerously high river discharges caused by extensive rainfall or snowmelt. Creating such predictions requires a hydrodynamic rainfall-runoff model of the river network. It is forced by forecasted rainfall amounts over a catchment. Water levels calculated by the model are juxtaposed with local warning levels in order to assess the threat posed by the event.

Alternately, the return period of the flood is calculated as an indicator of potential hazard. Currently it is becoming more common to calculate the exceedance of threshold with an uncertainty range. This is done by running several simulations with different rainfall forecasts (derived from the results of an ensemble of meteorological models). This method first became operational in Finland in 2000 and until 2010 was adopted by Sweden, Netherlands, France, Hungary and the pan-European EFAS system (Demeritt et al. 2010).

An example pathway is presented in Figure 3.4.1 and Figure 3.4.2. Swedish Meteorological and Hydrological Institute employs a hydrological model that covers even very small rivers and provides up to 8 days of forecasts (*hydrologisk nuläge*) of river discharges. In Figure 3.4.1 high river discharge (*vattenflöde*) on Ume River is forecasted for mid-July 2015. The current and forecasted water level (black line) is presented together with historically observed flows during 1981–2013, showing that higher flows were only observed once during that time period. In effect, warning was issued for parts of the Västerbotten (where Ume River is located), Jämtland and Norrbotten counties, indicating possibility of high river flows (*höga flöden*). The description explains the cause for the large discharges (snowmelt in parts of Scandinavian Mountains), indicating also that there is little risk of flooding.

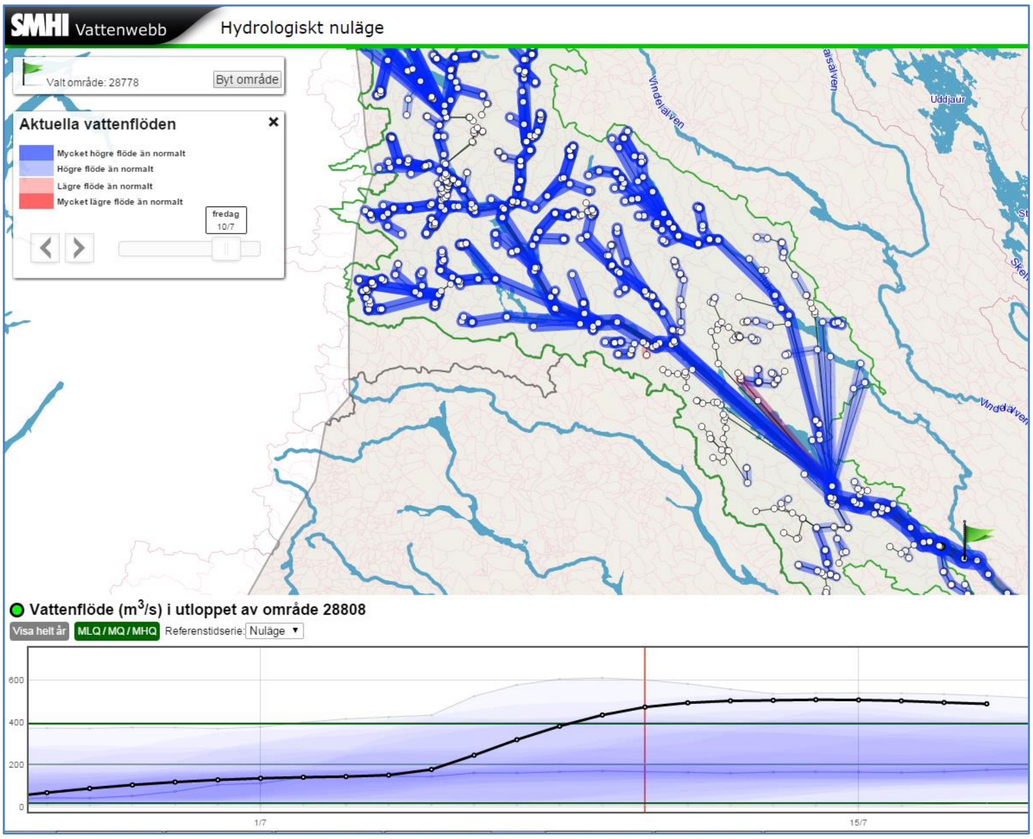
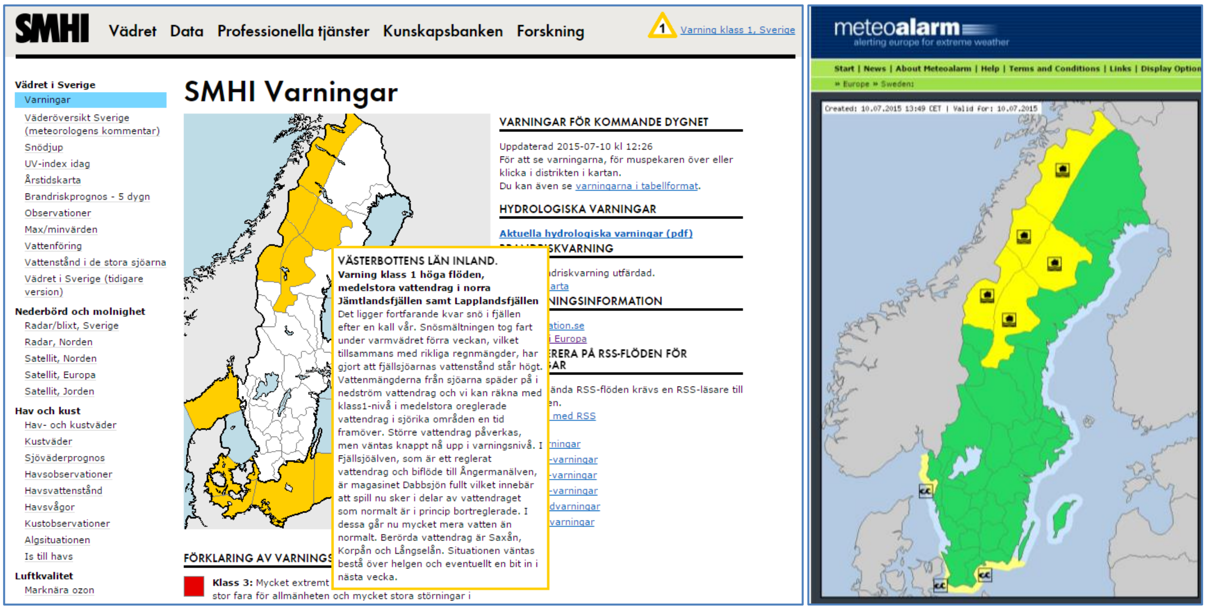


Figure 3.4.1. Hydrological forecasts from the Swedish Meteorological and Hydrological Institute, Ume River, July 2015 (SMHI 2015a).



VARNINGAR FÖR KOMMANDE DYGNET

Uppdaterad 2015-07-10 kl 12:26
För att se varningarna, för muspekaren över eller klicka i distrikten i kartan.
Du kan även se varningarna i tabellformat.

HYDROLOGISKA VARNINGAR

Aktuella hydrologiska varningar (pdf)

VÄSTERBOTTENS LÄN INLAND.

Varning klass 1 höga flöden, medelstora vattendrag i norra Jämtlandsfjällen samt Lapplandsfjällen

Det ligger fortfarande kvar snö i fjällen efter en kall vår. Snösmältningen tog fart under varmvädret förra veckan, vilket tillsammans med rikliga regnmängder, har gjort att fjällsjöarnas vattenstånd står högt. Vattenmängderna från sjöarna späder på i nedström vattendrag och vi kan räkna med klass1-nivå i medelstora oreglerade vattendrag i sjörika områden en tid framöver. Större vattendrag påverkas, men väntas knappt nå upp i varningsnivå. I Fjällsjöälven, som är ett reglerat vattendrag och biflöde till Ångermanälven, är magasinet Dabbsjön fullt vilket innebär att spill nu sker i delar av vattendraget som normalt är i princip bortreglerade. I dessa går nu mycket mera vatten än normalt. Berörda vattendrag är Saxån, Korpån och Långselån. Situationen väntas bestå över helgen och eventuellt en bit in i nästa vecka.

FÖRKLARING AV VARNINGS

🟥 **Klass 3:** Mycket extremt … stor fara för allmänheten och mycket stora störningar i

Figure 3.4.2. Warnings against high river discharges issued on 10 July 2015 for parts of northern Sweden (marked orange), on the SMHI website and the same warnings (marked yellow) transmitted to Meteoalarm, a pan-European warning system (SMHI 2015b, EUMETNET 2015).

The extent of forecasts is related with the availability of meteorological forecasts, therefore typically up to 1–2 weeks. In Finland, however, forecast of river discharges are available up to one year (Figure 3.4.3).

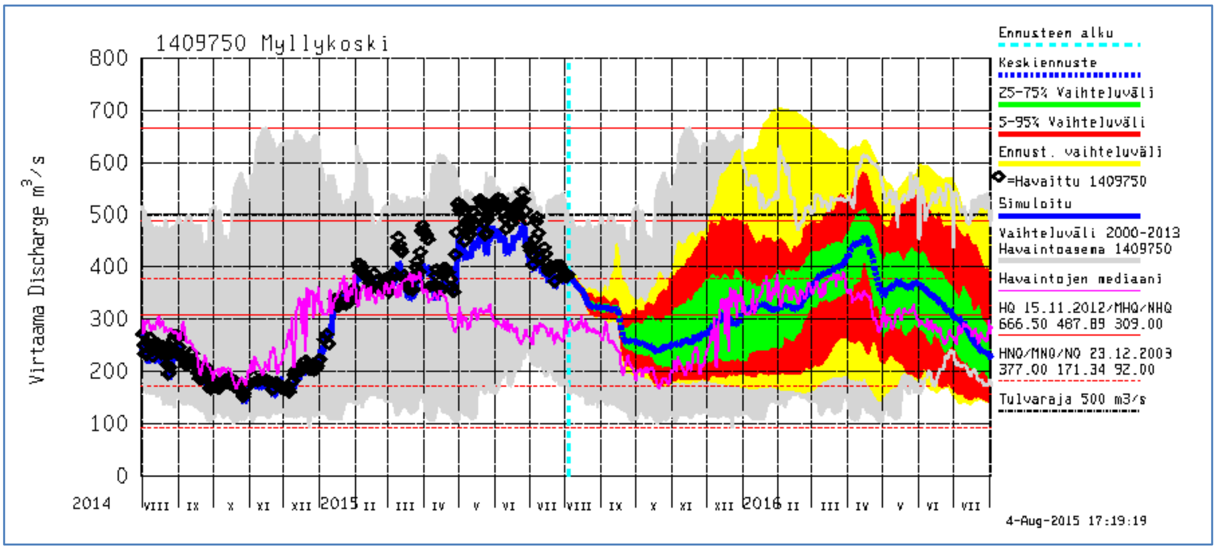


Figure 3.4.3. A Finnish yearly forecast for 2015-2016. Blue line is the mean simulation result, green area - the 50% confidence interval, red - the 90% interval, yellow – range of simulations, grey - the historical extremes (Environmental Administration 2015).

A pan-European flood modelling and warning currently exists, known as European Flood Alert System (EFAS), developed by Joint Research Centre (Thielen et al. 2009). It provides forecast and warnings up to 15 days. In Figure 3.4.4 the results of a probabilistic forecast made using LISFLOOD software in EFAS is presented. We can see that the river discharge is predicted to exceed mean high discharge.

However, EFAS itself does not disseminate warnings directly. Instead they are transferred to EFAS partners in 27 countries, who then use the information to issue warnings (EFAS 2015). A global extension of EFAS – GloFAS – is currently being tested (Alfieri et al. 2013).

Floods are also included on Meteoalarm website. However, only 8 out of 34 Meteoalarm participant countries provide such information[3]. Nevertheless, due to the obligation of producing flood alerts imposed by the EU, all countries issue them nationally, either using in-house hydrological computations or utilizing information retrieved from EFAS. Additionally, all countries included in Meteoalarm issue rainfall warnings, which in some areas can directly translate into risk of an urban flooding or flash flooding.

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[3] Austria, Czech Republic, France, Luxembourg, Montenegro, Netherlands, Sweden, Switzerland

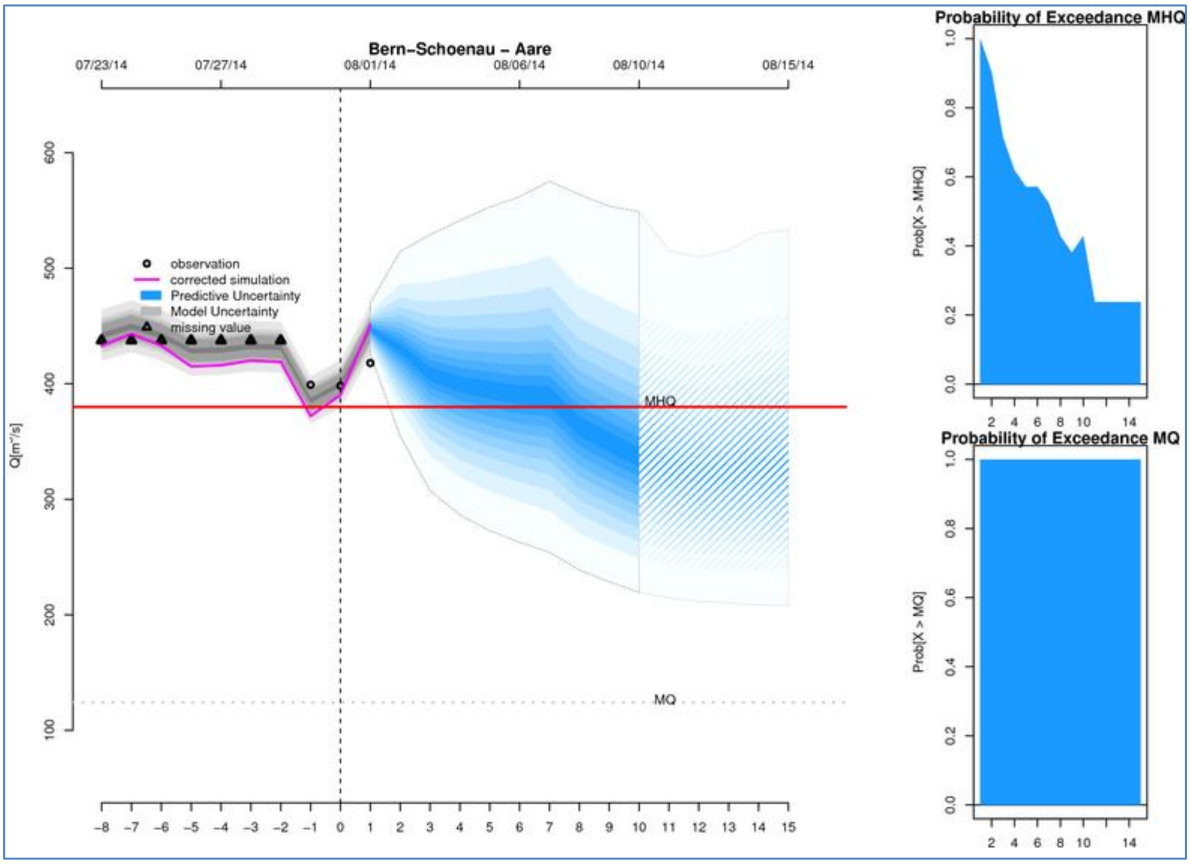

Figure 3.4.4. Probabilistic forecast of river discharges in Bern-Schoenau (Switzerland) and thresholds in EFAS (EFAS 2015).

Summary of the interviews

A total of 10 weather services out of 18 interviewed weather services provide warnings for river floods. Two out of 4 commercial weather services issues warnings. 4 weather services provide scheduled forecasts, of which 2 also provide additional warnings when necessary. Meanwhile, 4 organizations issue warnings only when it is necessary and the remaining 2 provide other irregularly issued products. The lead time of warnings is much diversified. Out of 8 weather services that provided information on their river flood warning systems' forecast range, half of them issue only short-term warnings (less than 3 days), including one only for very short-term (6-12 hours). The other half makes medium-term warnings. Warnings are mostly manually issued by a meteorologist, with 3 of the interviewees mentioning tailored warnings for infrastructure operators (including both commercial weather services which include river floods in their warnings).

From the user side, 23 out of 29 interviewed infrastructure operators consider river floods as a hazard to their assets or operations. However, only 8 of them use river flood forecasts (10 operators did not use forecasts at all or didn't answer to the question). 5 of them use medium-term forecast, while 4 utilize only short-term forecasts.

Warning thresholds

The threat posed by extreme river discharges depends heavily on local conditions, therefore warning thresholds are also defined locally. In the questionnaires, only two meteorological services mentioned their thresholds. Similarly to coastal floods, the approach can be twofold. Both weather services in the questionnaire use probabilities of exceedance as a warning threshold. Swedish

Meteorological and Hydrological Institute releases level 1 (lowest) warning if river discharge is predicted have a 2–10 year return period. If the river discharge is expected to be a 10-year event or rarer, level 2 (medium) warning is issued, and if discharge exceeds a 50-year return period, the level 3 (high) warning is disseminated. Czech Hydrometeorological Institute also mentions a 50-year return period as a threshold for extreme river discharge.

Aforementioned EFAS also utilizes a probabilistic approach to defining thresholds. There are four of them, and they are presented in Table 3.4.1. The cut-off values of return periods are 1.5, 2, 5 and 20 years. EFAS issues “flood alert” and “flood watch” warnings, however circumstances under which they are issued for depend on the terms agreed with each of EFAS’s partners. However, in case of flash floods, watches are issued if there is at least a 60% probability that the high threshold will be reached (ECMWF 2015b).

Table 3.4.1. EFAS warning thresholds (adapted from Thielen et al. 2009 and ECMWF 2015b).

Threshold		Description	Return period
Severe	🟪	Very high possibility of flooding, potentially severe flooding expected	> 20 years
High	🟥	High possibility of flooding, bank-full conditions or higher expected	> 5 years
Medium	🟨	Water levels high but no flooding expected	> 2 years
Low	🟩	Water levels higher than normal but no flooding expected	> 1.5 years

On the other hand, Polish Institute of Meteorology and Water Management defines thresholds separately for each river gauge, taking into account potential impacts of different water levels. Probabilistic approach is, however, more prevalent. Finnish Environmental Administration uses 3, 10 and 50 year return periods as definition of thresholds.

Availability of products

The availability of products and lead times, based on interviews and information on providers’ websites is summarized in Table 3.4.2. Public warnings for the short and medium term are commonly available, with tailored warnings for infrastructure operators occasionally available. Some weather services also provide warnings based on very short range forecasting systems. Additionally, routine forecasts (without warnings issued) are available for selected weather services up to and including a seasonal outlook. The European Flood Alert System provides warnings up to medium range for most of Europe (Figure 3.4.5) and pan-European hydrological forecasts up to extended range.

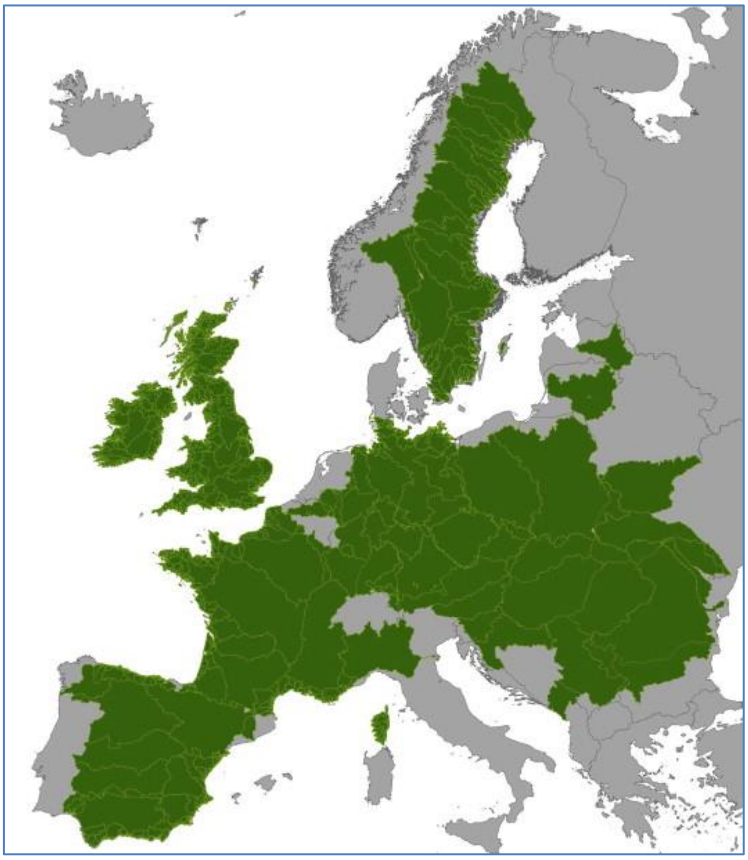

Figure 3.4.5. Coverage of EFAS. For green areas flood warnings are issued to EFAS's partners, while hydrological forecasting is done for entire Europe (Pappenberger et al. 2015b).

Table 3.4.2. Availability of warning products for river floods.

Availability of warning products (issued products)	River floods						
Forecasting ranges according to WMO	0 – 2 h, Now-casting	2 – 12 h, Very Short Range Fore-casting	12 – 72 h, Short Range Fore-casting	72 – 240 h, Medium Range Forecasting	10 – 30 d, Extended Range Fore-casting	1 – 3 m, 3 Month Outlook, Long Range Fore-casting	3 m – 2 y, Seasonal Outlook (departure from climate values)
Public warning products at a given schedule	-	-	+	+	-	-	-
Public warning products and updates issued at any time necessary (24 h continuous monitoring)	-	o	+	+	-	-	-
Tailored warning products for CI customers at a given schedule	-	-	o	o	-	-	-
Tailored warning products and updates for CI customers issued at any time necessary (24 h continuous monitoring)	-	-	-	o	-	-	-
Communication with CI customers on a case by case basis (no fixed agreement)	-	-	o	-	-	-	-
Routine general forecasts (no products for extreme weather events)	-	-	+	+	o	o	o

Source of WMO definitions: "DEFINITIONS OF METEOROLOGICAL FORECASTING RANGES", retrieved on 30 March 2015: http://www.wmo.int/pages/prog/www/DPS/GDPS-Supplement5-AppI-4.html

Availability categories:

-	Not available.
o	Available from some weather services in Europe.
+	Available from many weather services in Europe (standard product).
?	Unknown.

1.2.3 Predictability

The pan-European EFAS system is being regularly analyzed in terms of performance. The underlying hydrological model has good performance for catchments bigger than 300 km^2 and for all lead times (1–10 days). Lower accuracy is recorded in mountainous areas and some parts of Europe – mainly Mediterranean countries and Iceland (Alfieri et al. 2014). Currently, around 90% of 1-day forecasts predicting a river discharge above a 2-year return period (which is the threshold for medium/yellow warning) were estimated to be correct during recent validation (ECMWF 2015a). This value decreases to 70% for a 5-day lead time and 55% for 10 days. Figure 3.4.6 presents the performance of warnings (alerts and watches) issued since 2007. During that period EFAS became operational and expanded its membership, leading to an increase of warnings issued; flash flood warnings (only watches) were also introduced during that period (ECMWF 2015b).

Alerts are typically issued 3–4 days ahead of the expected peak (up to 6 days), while watches are usually distributed only 1–2 days before the event, or often on the day of the event. Flash flood warnings are issued usually 24–36 hours before the expected peak of rainfall (but occasionally up to 3 days). Most of the warnings are correct, and the percentage of false alarms has decreased compared to the early pre-operational phase.

According to Pappenberger et al. (2015a) the monetary benefit of flood warnings, based on EFAS system performance, is € 400 of avoided damages per € 1 invested in the system.

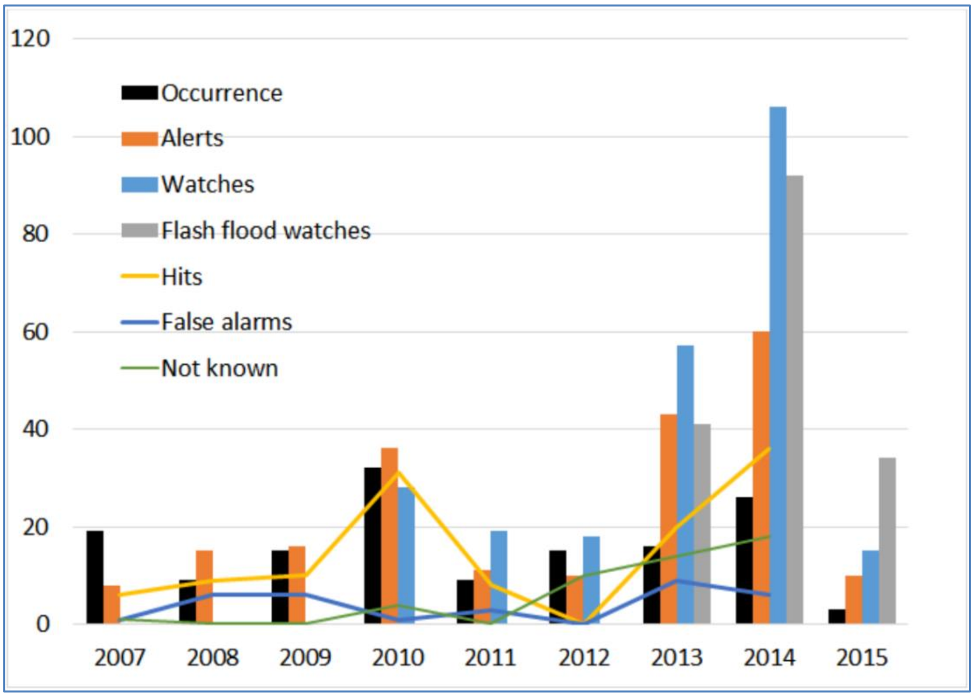

Figure 3.4.6. Performance of EFAS warning system, 2007–2015 (ECMWF 2015b).

Validation of national forecasting systems is not as thoroughly published as it is in the case of EFAS, though still some examples can be found. PEARP ensemble prediction system used by Météo-France includes a hydrological model SIM. It was analysed by Randrianasolo et al. (2010) who concluded that the system has “good performance” for 24 and 48 h forecasts. However, back then the flood warning system in France didn’t cover Nartuby and Argens rivers responsible for a flash flood that caused 26 fatalities on 15 July 2010. Only an orange rainfall warning was issued for that area; the catchments were added since then (Vinet et al. 2012). In Italy, Laiolo et al. (2014) analysed the skill of forecasts (12-48 hours ahead) provided by Flood-PROOFS system that is used since 2008 in Valle d’Aosta region. Their results indicate the difficulty of forecasting floods in the Alps. The system tends to produce many false alarms; however it rarely misses large river discharges.

Arheimer et al. (2011) review the sensitivities of the HBV model used for operational flood forecasting in Sweden since the 1970s. They indicate that using ensemble forecasts and auto-regressions help to improve the short-term forecasts significantly. Using radar precipitation data also improves predictions, as well as more regular re-calibration of the models when new data becomes available (operational models are sometimes not re-calibrated for many years).

3.4.4 Recommendations to improve the warning system

We see a potential for improvements in:

- Dissemination of warnings and forecasts by EFAS/GloFAS directly for the public instead of routing them through national agencies, which would also make the warnings directly available to CI customers.
- Combining river discharge predictions with flood hazards maps in order to make warnings more explicit about the area potentially affected by the flood.

3.4.5 Conclusions

To conclude, river flood warnings are now commonly disseminated and used in Europe. The performance of early warning systems is good; they provides valuable warnings, while being constantly improved thanks to advances in meteorological forecasting and observation systems.

Table 3.4.3. Skill of river flood warnings

Typical **Skill** of warning products (issued products)	River floods						
Forecasting ranges according to WMO	0 – 2 h, Now-casting	2 – 12 h, Very Short Range Fore-casting	12 – 72 h, Short Range Fore-casting	72 – 240 h, Medium Range Forecasting	10 – 30 d, Extended Range Fore-casting	1 – 3 m, 3 Month Outlook, Long Range Fore-casting	3 m – 2 y, Seasonal Outlook (departure from climate values)
Public warning products	-	+	+	+	-	-	-
Tailored warning products and updates for CI customers from land transport sector	-	-	o	o	-	-	-
Tailored warning products and updates for CI customers from energy sector	-	-	-	o	-	-	-
Tailored warning products and updates for CI customers from tele-communication sector	-	-	o	-	-	-	-

Skill categories:

-	Products not available or useless.
o	Little use for some applications.
+	Useful, strong additional value compared to mean climate information.
?	Unknown.

3.5 Heavy snowfall (and blizzards), snow loading, freezing rain

3.5.1 Introduction

Snowfall has large impact on transportation, causing traffic jams and delays, and severe accidents can happen on the highways. The rail traffic can also get disrupted especially by drifting snow in low temperatures, which trigger the rail points to get stuck and ice accumulation formed under the bottom of the coaches. Heavy snow (and snow loading) has negative impact also on energy and telecommunication networks, especially in the case of a blizzard, trees can fall over the power lines due to strong wind gusts and heavy snow. It is important that the meteorological services warn about these events in advance to allow different authorities to take mitigating action. The skill of Numerical Weather Prediction (NWP) models has improved substantially during the last couple of decades. For example, the verification results carried out at the Finnish Meteorological institute (FMI) show that the 2-day forecasts run by the HIRLAM (High Resolution Limited Area Model) model in 2012 were as good as (or even better than) the corresponding 1-day forecasts 20 years earlier (Eerola, 2013). The present models can forecast large scale low pressure areas and the related snowfall events quite well a couple of days ahead.

3.5.2 Assessment of warning systems

Weather warnings form an important component in the “toolbox” of the meteorologist. The significant information about high-impact weather phenomena can be disseminated to general public and different authorities, to allow mitigating action to be taken. Warnings typically cover a 24h time scale and are based either on national thresholds or international agreements (e.g. storm at sea: 10 minute mean wind speed ≥25 m/s). Early warnings are issued a couple of days ahead of potential weather hazards, giving additional time to raise readiness for the event. National Weather Services (NWSs) typically have the main responsibility of issuing weather warnings and those are updated whenever needed. The main information channels are TV, radio and internet. Warnings on European level are issued through the MeteoAlarm website (more information in Section 3.5.4).

Regarding winter weather events, the majority of NWSs issue warnings for **heavy snowfall** or **snow storms (blizzards)** as well as freezing rain, based on the Questionnaire for Weather Services arranged in RAIN Task 2.1. However, there is a large variation in the national warning criteria (or thresholds see Table 3.5.1). Many weather services have three warning levels based on the severity of expected impacts, which are typically different for different sectors of infrastructure, e.g. transportation or electric power supply. Already a few centimeters of snow can disrupt road traffic, but don’t normally cause any harm to distribution of electrical energy. In the other Questionnaire carried out in RAIN Task 2.1, targeted for Critical Infrastructure (CI) Operators, there were also large differences in the snowfall intensities that the interviewees had estimated to have negative consequences on infrastructure. Many of the interviewees had given a value of more than 20 cm/day for snow accumulation, which isn’t a common event in lowland areas. Based on the questionnaires, we suggest that the impact thresholds for snowfall derived here in the RAIN project are 6 cm/24h and 25 cm/24h (the former value, defined in RAIN Task 2.1, was 20 cm/24h). The lower threshold is linked to the impacts on transportation, the higher threshold more to the impacts on the energy and telecommunication sector. However, the impact of snow on CI depends also on the prevailing temperature conditions and wind force. During a blizzard, the strong wind causes drifting or blowing snow with very poor visibility and snow accumulation. The thresholds for the blizzard applied in the RAIN project (checked in Task 2.1) correspond with those defined in EU FP7 EWENT project: 24h snowfall ≥10 cm, maximum wind gust ≥17 m/s and daily mean temperature ≤0 °C.

Table 3.5.1. Warning thresholds for snowfall, based on the Questionnaire for Weather Services arranged in RAIN Task 2.1. As a reference, the impact thresholds defined in EU FP7 projects EWENT and RAIN (Task 2.1) are shown on the two bottom rows.

Level 1 (yellow)	**Level 2 (orange)**	**Level 3 (red)**	
25 cm/24h	50cm/24h	100 cm/24h	
5mm/6h (precipitation intensity of snowfall)	20 mm/12h	35 mm/12h	
1-4 cm	5-15 cm	>15 cm	
25 cm/12h (capital regions), 40 cm/24h (other regions)			
15 cm/1h			
7 cm/12 h or 15 cm/24h	3cm/1h or 6 cm/3h or 20 cm/24h or 30 cm/48h	5 cm/1h or 10 cm/3h or 30 cm/24h	
10 cm/12h (lowlands), 20 cm/12 h (mountain regions)	20 cm/12h (lowlands), 30 cm/12 h (mountain regions)	30 cm/12h (lowlands), 40 cm/12 h (mountain regions)	
10 cm/6h	15 cm/6h		
>0 cm (no time interval given)			
>10 cm (no time interval given)			
1 cm/24h	10 cm/24h	20 cm/24h	EU FP7 EWENT
6 cm/24h	25 cm/24h		EU FP7 RAIN

Table 3.5.2. Warning thresholds for freezing rain, based on the Questionnaire for Weather Services arranged in RAIN Task 2.1. The thresholds are based either on intensity or total ice accumulation. As a reference, the RAIN project's impact thresholds are shown on the bottom line.

Freezing rain, intensity (mm/h)			
Level 1 (yellow)	**Level 2 (orange)**	**Level 3 (red)**	
>0.5 mm/6h	>3 mm/6h		
Traces	<1 mm/h	≥1 mm/h	
Only occurrence warning			
0.5 mm/3h			
>0 mm/h			
Freezing rain, total ice accumulation (mm)			
Level 1 (yellow)	**Level 2 (orange)**	**Level 3 (red)**	
6 mm	20 mm		
Traces	<1 mm	≥1 mm	
0.0-19 mm	≥20 mm		
	severe >2 mm	extreme >7 mm	
Only occurrence warning			
5 mm	25 mm		EU FP7 RAIN

The weather services in Europe do not typically issue any special warnings for **snow loading**, but when forecasting heavy snowfall, the possibility of snow loading can be discussed in the outlooks or early warnings that are delivered to CI operators. This is the case for example in Finland. The two thresholds for snow loading defined in RAIN Task 2.1 are: 20 kg/m^2 and 60 kg/m^2.

The warning thresholds for **freezing rain**, based on the Questionnaire for weather services, are shown in Table 3.5.2. The variations are large also at this phenomenon. This might relate to the fact that some weather services are targeting their warnings to road traffic; in that case an ice accumulation of 1 mm can already be very dangerous, other weather services might focus more on the energy sector when using much higher thresholds (e.g. 20 mm for the level 2 warning). The thresholds defined in RAIN project are 5 mm and 25 mm for total ice accumulation.

Table 3.5.3 shows the availability of warning products and lead times (based on the Questionnaire for Weather Services/ RAIN Task 2.1). Most weather services issue a warning for heavy snowfall using at least a 24h lead time. Many weather services also have tailored warning products ("early warnings") for Critical Infrastructure (CI) customers with several days' lead times; about 60% of the interviewed weather services use a lead time of 2 days or more. In the case of freezing rain the warning lead times appeared to be on average somewhat shorter. The FMI issues outlooks with a 3 day lead time and, in addition, there is a web-based service where various customers can get preliminary information (probabilities) of possible weather hazards 5-10 days in advance. Most weather services also issue routine general forecast products up to 10 days ahead, some of them even in the monthly or seasonal time scale. However, these general forecasts normally don't include any products of high-impact weather events.

3.5.3 Predictability

NWP models are generally known to lose their forecasting skill during the course of forecast lead time due to at least the following three prominent factors:

- (i) Growth of errors starting from the initial conditions of NWP models, i.e. relating to initial uncertainties
- (ii) Ability of NWP models to provide only an approximation (albeit a good one) of the laws of physics in the atmosphere, i.e. relating to inherent model uncertainties
- (iii) Model error growth, i.e. predictability is very much weather and flow pattern (cyclones, anticyclones, westerlies etc.) dependent relating to the chaotic nature of the atmosphere.

There are numerous various ways to examine atmospheric predictability by NWP models. As an example, a quite simplistic way to define the "deterministic limit" of binary, threshold-based deterministic forecasts is by distinguishing the point in forecast lead time beyond which forecasts are more likely to go wrong than go right. In other words, when "hits" equal "misses + false alarms" in a two-by-two contingency table, that is when the verification measure Threat Score (also known as Critical Success Index), TS = 0.5. (For more details see e.g. Nurmi, 2003). When looking at extreme (rare) weather events (e.g. 12-hour accumulated precipitation of more than 50 mm in a climatologically dry location), a simple measure like the TS is seldom of practical use following its definition of not being able to properly tackle rare events. The predictability of extreme/rare events, especially at specific, defined regions or locations is difficult to quantify posing thus a highly challenging forecast verification issue. Novelty verification measures like, e.g. the Symmetric Extremal Dependence Index (SEDI) can prove to be helpful in this respect (Nurmi et al, 2013; North et al, 2013).

Table 3.5.3. Availability of warning products for heavy snowfall and the blizzard

Availability of warning products (issued products)	**Heavy snowfall and blizzard**						
Forecasting ranges according to WMO	0 – 2 h, Now-casting	2 – 12 h, Very Short Range Fore-casting	12 – 72 h, Short Range Fore-casting	72 – 240 h, Medium Range Forecasting	10 – 30 d, Extended Range Fore-casting	1 – 3 m, 3 Month Outlook, Long Range Fore-casting	3 m – 2 y, Seasonal Outlook (departure from climate values)
Public warning products at a given schedule	?	+	+	o	-	-	-
Public warning products and updates issued at any time necessary (24 h continuous monitoring)	+	+	+	?	-	-	-
Tailored warning products for CI customers at a given schedule	+	+	+	o	?	-	-
Tailored warning products and updates for CI customers issued at any time necessary (24 h continuous monitoring)	+	+	+	o	-	-	-
Communication with CI customers on a case by case basis (no fixed agreement)	?	?	?	?	?	?	?
Routine general forecasts (no products for extreme weather events)	+	+	+	+	o	o	o

Source of WMO definitions: "DEFINITIONS OF METEOROLOGICAL FORECASTING RANGES", retrieved on 30 March 2015: http://www.wmo.int/pages/prog/www/DPS/GDPS-Supplement5-AppI-4.html

Availability categories:

-	Not available.
o	Available from some weather services in Europe.
+	Available from many weather services in Europe (standard product).
?	Unknown.

Nevertheless and as already mentioned in Section 3.5.1, forecast skill has improved substantially during the past 20-30 years. As evidence, Figure 3.5.1 shows the improvement of predictability of the free atmosphere circulation patterns (pressure ridges, troughs, jet streams etc.) based on the ECMWF (European Centre for Medium-range Weather Forecasts; www.ecmwf.int) deterministic forecast system. The red curve indicates how predictability has increased by 2.5 days since the early 1990s and is expected to reach 8 days by 2030. This is based on the commonly used verification measure of the anomaly correlation (ACC) between forecast and observed atmospheric features remaining above the pre-defined 80% level. Consequently, predictability improvement by one day per decade is a commonly accepted outlook. However, atmospheric predictability is far from being a trivial issue as already discussed above. The blue curve in Figure 3.5.1 follows the assumption that predictability was pre-defined by the ACC remaining above the 60% level. This was the threshold which was followed in NWP verification practice during many decades, until quite recently. This makes things even more interesting and debatable, first by realizing that based on this criterion the ECMWF model predictability would reach 10 days by 2030 and, secondly, noting that ECMWF produces deterministic forecasts only up to 10 days. Considering this, free atmosphere predictability would appear to be at a higher level than what the deterministic NWP model(s) would actually produce - a dilemma indeed. One might further argue by looking at Fig. 3.5.1 that the improvements in forecast quality have leveled off during the past couple years, so maybe after all the one day per decade “trend” will not necessarily materialize to the future.

Moving beyond forecast lead times of more than approximately a week generally supports the practice of shifting from deterministic forecasting to the use of probabilistic forecast information. The ECMWF ensemble prediction system (ENS) involves 52 parallel forecasts which are run starting from slightly different initial conditions. The effects of small errors and uncertainties in the initial analysis can thus be simulated by adding small perturbations into the initial analyses. This method produces a range of values (rather than a single deterministic solution) and, consequently, a set of probabilistic forecast distributions for different weather variables. Both the deterministic forecast (up to 10 days) and the ENS (up to 15 days) system are run twice daily at ECMWF. Based on the ENS method, longer range, monthly forecasts are run twice a week and seasonal forecasts once a month. Many other operational weather centers (e.g. UK Met Office, Meteo France, NOAA/NCEP in the USA) run their own comparable forecasting systems.

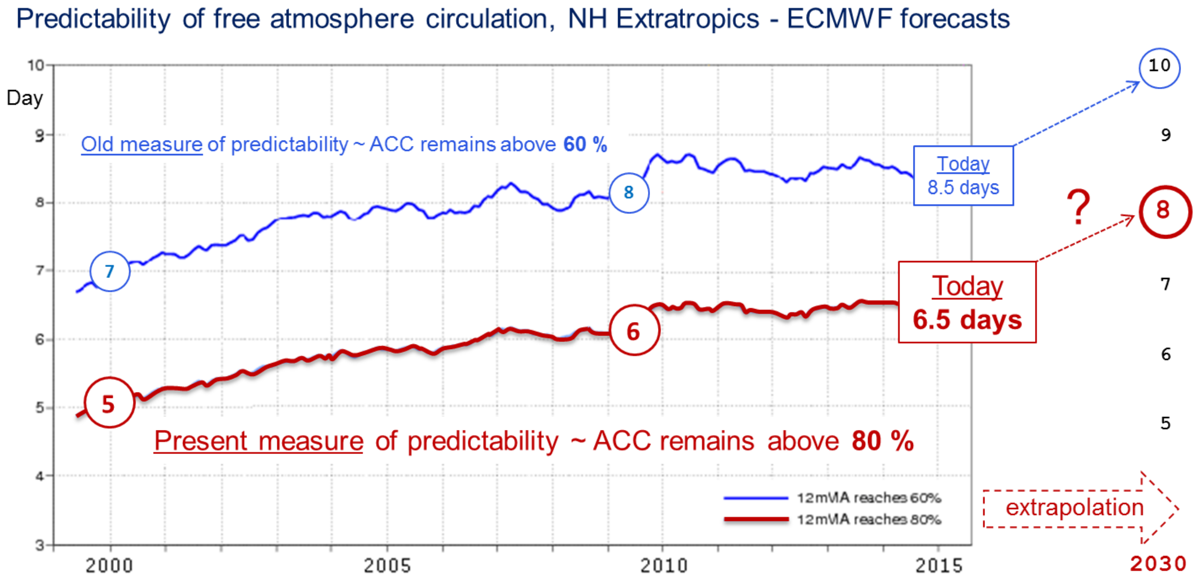

Figure 3.5.1. Evolution of the predictability (in number of days) of the large-scale free atmospheric circulation by the ECMWF deterministic forecast system covering the past 15 years and an extrapolated estimate towards 2030 (highlighted with question mark). The verification is over the northern hemisphere extratropics based on Anomaly Correlation (ACC) and by adapting two thresholds, 60 % (in blue) and 80 % (red curve). The predictability was 4 days in the early 1990s (not shown) based on the 80 % ACC threshold. (Source: ECMWF)

When it comes to specific surface weather variables like precipitation or surface temperature, their predictability is clearly lower than those of the large-scale atmospheric flow patterns. As an example, Figure 3.5.2 shows how the predictability of precipitation is today about 4 days and is estimated to reach 5.5 days by 2030, averaged over the entire extratropical northern hemisphere. Also here there is a clear "leveling-off" of the long-term positive trend which may open up many questions about predictability in future climates. When down-scaling the verification statistics which cover large geographic regions to a more local scale the cases can be quite different depending on the area, latitude, topography, land-sea distribution etc. This is showcased by Figure 3.5.3, for Europe, where the long-term trend in past history is still evident but less smooth than in the larger scale scope, and fluctuations during the course of years are much more prominent, especially during the past five or so years.

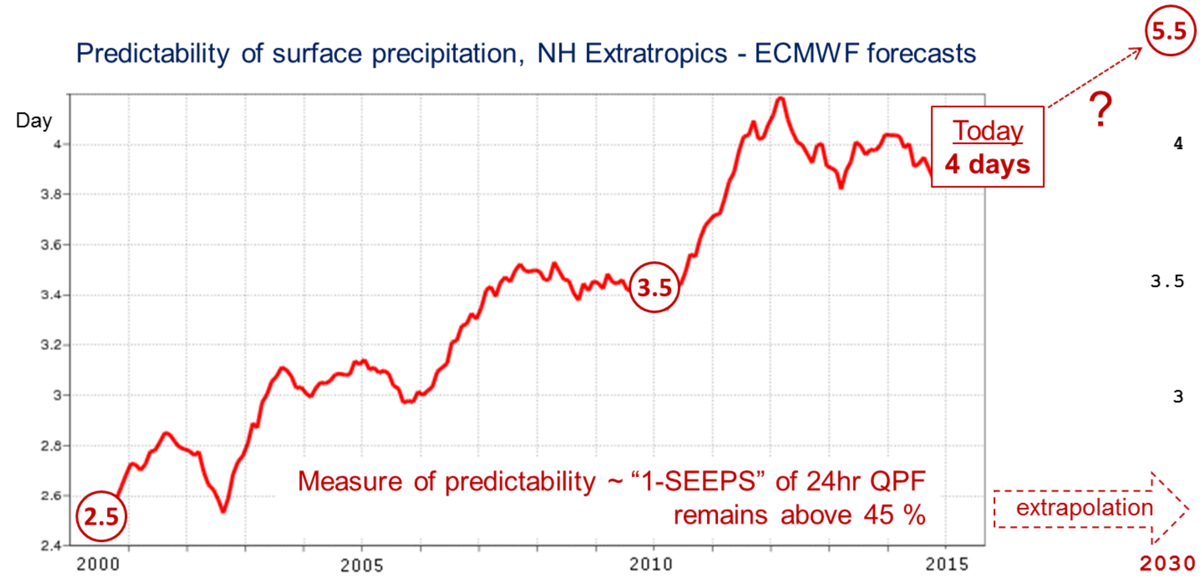

Figure 3.5.2. Evolution of the predictability (in number of days) of surface precipitation by the ECMWF deterministic forecast system covering the past 15 years and an extrapolated estimate towards 2030 (highlighted with question mark). The verification is over the northern hemisphere extratropics. The measure of predictability is the ECMWF official headline score, "1-SEEPS" of 24hr accumulated precipitation remaining above 45%. The predictability was 2 days in the mid-1990s (not shown). (For definition of "1-SEEPS", see Rodwell et al, 2010 or North et al, 2013). (Source: ECMWF)

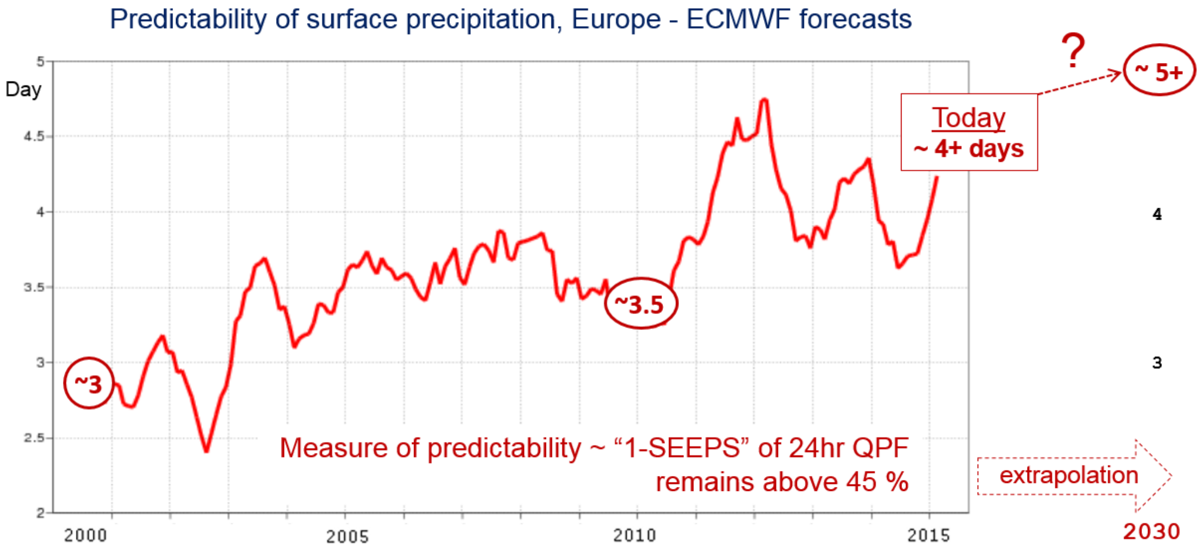

Figure 3.5.3. As Figure 3.5.2 but averaged over Europe.

A rough estimate of the skill of weather warning products is presented in Table 3.5.4. The warning products up to 72 hours or forecast time are found useful, and the warning products appear to still be useful in the medium range for some applications. However, it is difficult based on the Questionnaires to find any clear differences in the usefulness of the products between customers from different CI sectors (land transport, energy, and telecommunication).

Table 3.5.4. Estimated skill of products for different lead times and CI sectors, based on the Questionnaires for weather services and stakeholders carried out in RAIN Task 2.1 and literature review (forecasting experience etc.).

Typical **Skill** of warning products (issued products)	**Heavy snowfall and the blizzard**						
Forecasting ranges according to WMO	0 – 2 h, Now-casting	2 – 12 h, Very Short Range Fore-casting	12 – 72 h, Short Range Fore-casting	72 – 240 h, Medium Range Forecasting	10 – 30 d, Extended Range Fore-casting	1 – 3 m, 3 Month Outlook, Long Range Fore-casting	3 m – 2 y, Seasonal Outlook (departure from climate values)
Public warning products	+	+	+	-	-	-	-
Tailored warning products and updates for CI customers from land transport sector	+	+	+	o	-	-	-
Tailored warning products and updates for CI customers from energy sector	+	+	+	o	-	-	-
Tailored warning products and updates for CI customers from tele-communication sector	+	+	+	o	-	-	-

Skill categories:

-	Products not available or useless.
o	Little use for some applications.
+	Useful, strong additional value compared to mean climate information.
?	Unknown.

The Finnish Meteorological Institute (FMI) has developed an in-house, on-line, real-time verification system to monitor forecast skill on a continuous, regular basis covering the “official” forecasts and warnings as well as NWP model output. This system can also be used to study the ability of models to predict high impact weather events. When it comes to early warnings, it is important to know the forecast skill of NWP models in the time-frame of 2-5 days ahead. Figure 3.5.4 shows an example of heavy snowfall events during four winters in southern Finland and the corresponding ECMWF +54 hour forecasts of 24 hour accumulated precipitation. The selection of cases is based on the following criteria at Helsinki-Vantaa airport: daily mean temperature ≤ 0 ^{o}C, 24 hour precipitation ≥ 6 mm (i.e.

the first threshold for heavy snowfall defined in Task 2.1 of RAIN project). The ECMWF ”two-day” forecasts were highly successful in these cases as seen in Figure 4 and the precipitation amount was underestimated only in a couple of cases. Heavy snowfall events are mostly related to large scale low pressure systems which can be captured quite well a couple of days ahead by present NWP models. Local heavy snowfalls (e.g. sea-effect snowfall induced by open sea-surface in cold conditions) are much trickier to forecast properly but can be predicted relatively well by high resolution limited area models.

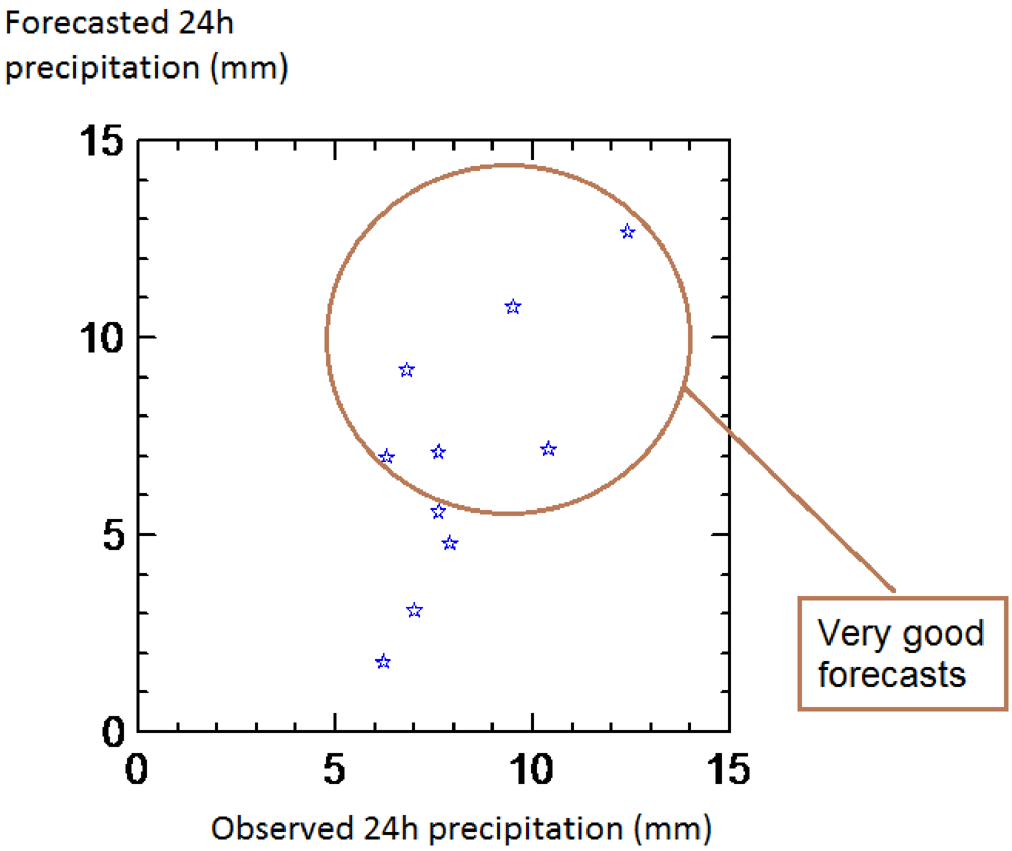

Figure 3.5.4. Scatter plot of heavy snowfall events at Helsinki-Vantaa airport during four winters (November-March, 2011/12-2014/15), showing observed precipitation amount (horizontal axis) against deterministic ECMWF +54h forecasts (00 UTC run) accumulated 24h precipitation forecasts (vertical axis). Only cases with observed precipitation ≥6 mm/24h and daily mean temperature ≤0 °C are included.

Snow loading can have serious impacts causing forest damages and breaks of power transmission lines. Snow loading occurs typically at temperatures close the zero degrees and between 0 and 0.5 °C combined with precipitation. Thus, snow loading is more difficult to forecast than the occurrence of heavy snowfall only, because one has to predict both the precipitation amount and the local temperature conditions accurately. Figure 3.5.5 shows the verification of ECMWF 60 hour temperature forecasts during year 2014 for Helsinki-Vantaa airport. In general, the results look quite good with the bias being small and values on the scatter plot mostly close to the diagonal. However, there is some scatter evident at forecasted and observed temperatures around 0 °C indicating that the exact precipitation form (dry or wet snow, sleet or rain) could be missed with a relatively small error in the temperature forecast.

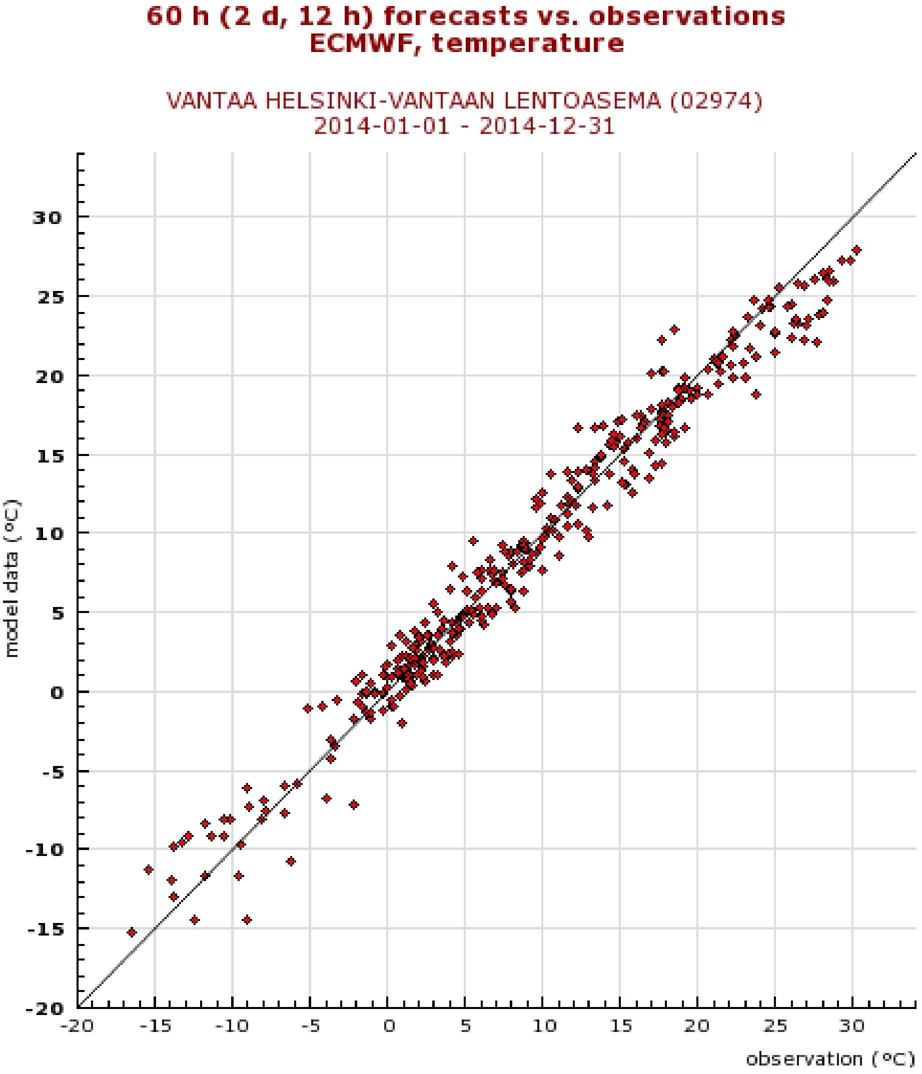

Figure 3.5.5. Scatter plot of deterministic ECMWF +60h two meter temperature forecasts (vertical axis) against observations at Helsinki-Vantaa airport in Southern Finland. The forecasts are from the 00 UTC run and cover the year 2014. Scores: ME = -0.15 °C, MAE = 1.35 °C.

3.5.4 Other warning products

Weather warnings are issued on European level by the **EUMETNET MeteoAlarm service** (www.meteoalarm.eu). It is a co-operative initiative by more than 30 National Weather Services (NWS) in Europe. Colour-coded maps of Europe show where the weather is expected to become dangerous. All the countries included have agreed on similar colour coding based on likely impacts and danger. The colour coding is as follows: **Green**: Nothing to worry about; **Yellow**: Potential danger; **Orange**: Dangerous situation; **Red**: Great danger due to extremely severe weather. For each weather variable (e.g. snowfall), meteorological “impact thresholds” define the colour to be assigned. These thresholds are set by the NWS in charge for the region, and they are naturally at least somewhat different in different countries. The user gets more detailed information about the expected weather hazard by clicking an area on the map. The warnings cover a 24 hour (48 hour) period and are updated several times a day by the NWSs that are responsible for their specific forecasting areas.

3.5.5 Improving the warning system

The forecasting process can always be further developed. For example, NWP model data can be processed with meteorological work stations by manual edition or using the so-called SmartTools, which are post-processing scripts developed by FMI forecasters (Neiglick et al., 2014). The edited NWP data forms the basis of various customer products like warnings. Moreover, the role of weather impact forecasting will become more pronounced in the foreseeable future with the forecasts and warnings including more implications and explanations about the expected weather event inducing potential harmful impacts to infrastructures, e.g. transportation, energy etc. There are already various such applications under development and some even in close to practical production. One such application was developed under the EU 7th Framework Programme project FOTsis, where the operational road weather forecasting system initially developed at FMI for Finnish roads was further developed and translated into a weather impact forecasting framework covering specific road stretches in different European countries to produce and forward guidance information to end-users against adverse road weather events (see Atlaskin et al, 2015 and Mylne et al, 2015).

The recently launched WMO World Weather Research Program (WWRP) High Impact Weather (HIW) Project is an important multi-faceted collaborative international initiative to look into issues dealing with high impact weather events and covering disruptive winter weather as well as predictability and forecast verification issues.

3.5.6 Conclusions

Forecast skill has improved substantially in the short and medium range during the past 20 years following model resolution improvements and computer power enhancements. For example, the increased computer capacity at FMI has made it recently possible to run the high resolution limited area model “HARMONIE” in a “rapid update cycle” eight times a day. All this achievements enable development of effective warning services, early warnings and outlooks, accurate warnings in the 24 hour range with continuous follow-ups and updates and also impact forecasting applications.

3.6 Wildfires (forest fires)

3.6.1 Introduction

Wildfires are a global problem, in many parts of Europe long dry spells often result in wildfires (or forest fires). Especially in southern Europe large areas can get burned due to hot and dry summer weather, as happened during summer 2015 in Portugal for example. In the northern boreal forests most of the fires occur in Russia, Canada and Alaska in spite of progressive fire management programs (Stocks et al. 2008), while in northern Europe typically smaller areas are affected by forest fires, although there are exceptions, for example the large wildfire in Västmanland, Sweden, in summer 2014 (this event is presented in RAIN D2.2).

Most of the wildfires are ignited by humans, but there are also natural causes for fires, for example a lightning strike. Large wildfires often have widespread adverse effects as the smoke and related small particles can be advected long distances by air steams, thus having a negative impact on human well-being. In spring and summer 2006 the air quality in southern Finland was badly affected by two fire smoke episodes, which lasted altogether several weeks (Anttila et al., 2008). Also in July 2010, when the very hot weather induced fires in western Russia, the advection of smoke affected large areas in Eastern Europe. Many countries have developed forecasting methods to assess the risk of forest fires and the aim is to warn general public and different authorities well in advance for conditions that are favorable for fire ignition.

3.6.2 Assessment of warning systems

Fire danger can be assessed by using methods that produce qualitative and/or numeric indices of the level of fire potential. The risk for fires depends on the moisture of soil surface layer, which is determined by preceding and prevailing weather conditions. A large number of various methods to predict forest fire risk have been developed. One of the most widely used methods in Europe is Van Wagner’s (1987) Forest Fire Weather Index (FWI), which was developed in Canada. Calculation of FWI requires daily observations of accumulated precipitation, temperature, relative humidity and wind speed. FWI was originally divided in six fire danger classes (Table 3.6.1), representing fire behaviour in a generalized standard fuel type. The FWI class scale should always be fitted to regional conditions. The FWI has been successfully introduced to different European environments, e.g. Spain and Greece (see RAIN document M2.1: List of definitions and thresholds). Other common fire indices in Europe are listed by Camia and Bovio (2000).

In Finland, the FMI operationally monitors conditions favourable for forest fire potential, and issues a public forest fire warning when the calculated index describing fire danger, FFI (Forest Fire Index), exceeds a certain threshold (Vajda et al., 2013). The FFI is determined from the surface moisture by estimating the volumetric moisture of a 60 mm thick soil surface layer using potential evaporation and precipitation data. The scaling of the FFI is shown in Table 3.6.2.

Table 3.6.1. The original FWI class ranges (Van Wagner, 1987)

Danger class	FWI range
Extreme	>29
Very high	17-29
High	9-16
Moderate	5-8
Low	2-4
Very low	0-1

Table 3.6.2. Scaling of the volumetric moisture fraction (volume of water content/volume of soil) into surface wetness class and Forest Fire Index (FFI), see Vajda et al., 2013.

FFI	Volumetric moisture	Moisture status
6.0	0.10	Very dry
5.9-5.0	0.11-0.14	Dry
4.9-4.0	0.15-0.19	Moderately dry
3.9-3.0	0.20-0.25	Moderately wet
2.9-2.0	0.26-0.32	Wet
1.9-1.0	0.33-0.50	Very wet

As already mentioned, the FWI scale should be fitted to regional conditions. Table 3.6.3 shows the adjusted scale of the FWI corresponding with the scale of the FFI (Vajda et al., 2013). The two scales were adjusted using the results from previous fire ignition tests, and a frequency distribution from the resulting rating levels generated. The threshold of forest warning is 10 for the FWI and 4 for the FFI.

Based on the Questionnaire for Weather Services (RAIN Task 2.1), most of the forest fire warnings (75%) cover a time scale of 1-2 days. A couple of weather services issue also early warnings. A summary of the availability of forest warnings is shown in Table 3.6.4. A shortage in the Questionnaire concerning forest fires is the low number of answers (8), so we can't draw any precise conclusions based on that.

In addition to issuing the warnings on national level, eight countries (situation at the end of September 2015) deliver forest fire warnings also to the EUMETNET Meteoalarm system (www.meteoalarm.eu). That is a low number, because in total 34 countries are involved in Meteoalarm. Another source for European wide information about fire risk and occurrence is the European Forest Fire Information System (EFFIS), which is provided by the JRC (Joint Research Centre) and is available at http://forest.jrc.ec.europa.eu/effis. The service includes most up to date information on the current fire season in Europe and in the Mediterranean area, e.g. the current meteorological fire danger maps and forecast up to 6 days.

Table 3.6.3. The adjusted scale of FWI corresponding with the scale of FFI (Vajda et al., 2013).

	FWI		**FFI**	
No fire danger	1	0-1.9	1	1.0-1.9
	2	2-9.9	2	2.0-2.9
			3	3.0-3.9
Fire danger	3	10.0-17.9	4	4.0-4.9
	4	18.0-24.9	5	5.0-5.9
	5	>25.0	6	6.0

3.6.3 Predictability

There have only been quite few studies published about the skill of forest fire indices in Europe. At the FMI, the Finnish Forest Fire index FFI has been evaluated and found to predict fire danger better in southern part of Finland than in north (Vajda et al., 2013). The Finnish index FFI and the Canadian index FWI have been compared (Vajda et al., 2013; Giannakopoulos et al., 2006). In general, FWI and FFI determine a fairly similar fire risk for a set of weather readings (correlation r= ca. 0.7). Higher correlations were found especially for locations under significant fire risk. However, in northern Finland FWI gave almost doubled the amount of high fire danger events than compared to FFI.

In principle, the skill of forest fire indices is related to the skill of Numerical Weather Prediction models to predict precipitation, temperature, humidity and wind. The forest fire warnings have strong additional value in the short range (up to 72 h), both for the public and CI customers. However, how different CI sectors benefit from the products (Table 3.6.5) doesn’t come up from the Questionnaires carried out in RAIN Task 2.2.

Table 3.6.4. Availability of wildfire/forest fire warnings and outlooks.

Availability of warning products (issued products)	Wildfire/ forest fire warnings						
Forecasting ranges according to WMO	0 – 2 h, Now-casting	2 – 12 h, Very Short Range Fore-casting	12 – 72 h, Short Range Fore-casting	72 – 240 h, Medium Range Forecasting	10 – 30 d, Extended Range Fore-casting	1 – 3 m, 3 Month Outlook, Long Range Fore-casting	3 m – 2 y, Seasonal Outlook (departure from climate values)
Public warning products at a given schedule	-	-	+	?	-	-	-
Public warning products and updates issued at any time necessary (24 h continuous monitoring)	?	?	o	?	-	-	-
Tailored warning products for CI customers at a given schedule	?	?	+	o	?	-	-
Tailored warning products and updates for CI customers issued at any time necessary (24 h continuous monitoring)	?	?	o	?	-	-	-
Communication with CI customers on a case by case basis (no fixed agreement)	?	?	o	?	?	-	-
Routine general forecasts (no products for extreme weather events)	+	+	+	+	o	o	o

Source of WMO definitions: "DEFINITIONS OF METEOROLOGICAL FORECASTING RANGES", retrieved on 30 March 2015: http://www.wmo.int/pages/prog/www/DPS/GDPS-Supplement5-AppI-4.html Availability categories:

-	Not available.
o	Available from some weather services in Europe.
+	Available from many weather services in Europe (standard product).
?	Unknown.

Table 3.6.5. Skill of issued warning products

Typical **Skill** of warning products (issued products)	Wildfires/Forest fires						
Forecasting ranges according to WMO	0 – 2 h, Now-casting	2 – 12 h, Very Short Range Fore-casting	12 – 72 h, Short Range Fore-casting	72 – 240 h, Medium Range Forecasting	10 – 30 d, Extended Range Fore-casting	1 – 3 m, 3 Month Outlook, Long Range Fore-casting	3 m – 2 y, Seasonal Outlook (departure from climate values)
Public warning products	-	-	+	?	-	-	-
Tailored warning products and updates for CI customers from land transport sector	?	?	?	?	?	?	?
Tailored warning products and updates for CI customers from energy sector	?	?	?	?	?	?	?
Tailored warning products and updates for CI customers from tele-communication sector	?	?	?	?	?	?	?

Skill categories:

-	Products not available or useless.
o	Little use for some applications.
+	Useful, strong additional value compared to mean climate information.
?	Unknown.

3.6.4 Recommendations to improve the warning system

The forest fire indices should be continuously verified and more research and development should be carried out. One way to develop the indices could be an application, where (the type of) vegetation would be taken into account in the fire risk calculations. Regarding the METEOALARM warning service, more countries should offer their forest fire warnings via the service.

3.6.5 Conclusions

Wildfires can cause big harm for the society. Some CI Operators mentioned that wildfires can disrupt land transport (train/bus traffic), e.g. when there is fire on embankments. Dense smoke can also be harmful. It is important that fire risk indices are developed and operationally run at the weather services so that different operators get a fire risk warning when necessary and can raise readiness for the probable fire event.

3.7 Hail

3.7.1 Introduction

Hail exclusively occurs with deep moist convection, which usually produces lightning and thunder. Not all convective storms produce hail that reaches ground level, as the hail may melt before it reaches the surface. Some hailstorms are responsible for immense financial losses, injuries and, rarely, fatalities (Kühne and Groenemeijer, 2015). Two hailstorms in Germany on the 27th and 28th of July 2013 ranked as the costliest weather event worldwide in the year 2013 according to the reinsurance sector (Kunz et al., 2013; Munich RE, 2014).

The damage potential is both related to the size and to the number of hailstones. At a maximum diameter of 2 cm (referred to as “large hail”) damage starts to become significant. The risk for serious injuries and exceptional damage rises strongly with hail diameters of more than 5 cm (referred to as “extremely large hail”). Large hail most often occurs with organized convection, extremely large hail occurs exclusively with supercells, a strictly organized form of convection.

Critical Infrastructure may be impacted by large hail when structural damage occurs. A typical example is the smashing of glass fronts or roofs of railway stations, airports or control rooms of any sort. Subsequently, heavy rain and hail can enter such structures, driven by strong wind gusts that often accompany hailstorms. In addition, large hail can also crush windows of locomotives or buses or damage railway signaling equipment.

Damage may also occur with hail sizes of less than 2 cm, especially if the amount of hail is large. Hail accumulations on the ground of more than 20 cm (mean depth of the hail layer) have been observed. Large amounts of relatively small hail do not only devastate agriculture, but may also affect critical infrastructure, such as when roads and railways become impassable. In such cases, snow ploughs need to be activated in the mid of summer.

The functionality of urban infrastructure can be heavily affected when hail clogs the drainage systems, which causes or aggravates the flooding of underground passages and underground infrastructure like subways. The RAIN report “Past Cases of Extreme Weather Impact on Critical Infrastructure in Europe” highlights such a case, in which roads, underpasses and underground infrastructure of the city of Stuttgart (Germany) were severely affected for many hours after a hailstorm on the 15th of August 1972 (Groenemeijer et al., 2015). This report also highlights the possible impact of large hailstones to photovoltaic systems and the consequences for the local electricity production.

3.7.2 Assessment of warning systems

Numerical Weather Prediction

The forecasts of operational Numerical Weather Prediction (NWP) models, which are routinely available to weather forecasters and forecasting systems, do generally not model hail explicitly. This is because hail development cannot be simulated on the grid spacing of typical NWP models. Although regional high-resolution NWP models (with horizontal grid spacing on the order of 1-4 km) may be configured to simulate hail development (e.g. Seifert and Beheng, 2006), they are only used experimentally because of their high computational cost. Nevertheless, NWP models are useful for forecasting large hail, because i) the responsible convective storms can with some accuracy be forecast by regional high-resolution models, even if hail formation itself not modelled, and because ii) the general conditions that favour such storms can be forecast at even lower resolution (and with longer lead times) by global models.

An accurate forecast of hail occurrence thus relies on the capability of forecasters or forecast systems to accurately interpret NWP model output into a forecast of hail. In that light, convection permitting high-resolution NWP models are increasingly able to distinguish between different types of convective storms, some of which are more likely to produce (large) hail than others. In particular, the prediction of intense discrete rotating cells can give a hint that supercells, which often produce very large hail, may occur (see figure 3.7.1). These models cannot be expected to predict the exact location of storms and may have biases in the number of storms they simulate. For instance, such models occasionally have a general reluctance to develop convective storms. A forecast of hail that would be purely based on such a model, would consequently be of low quality.

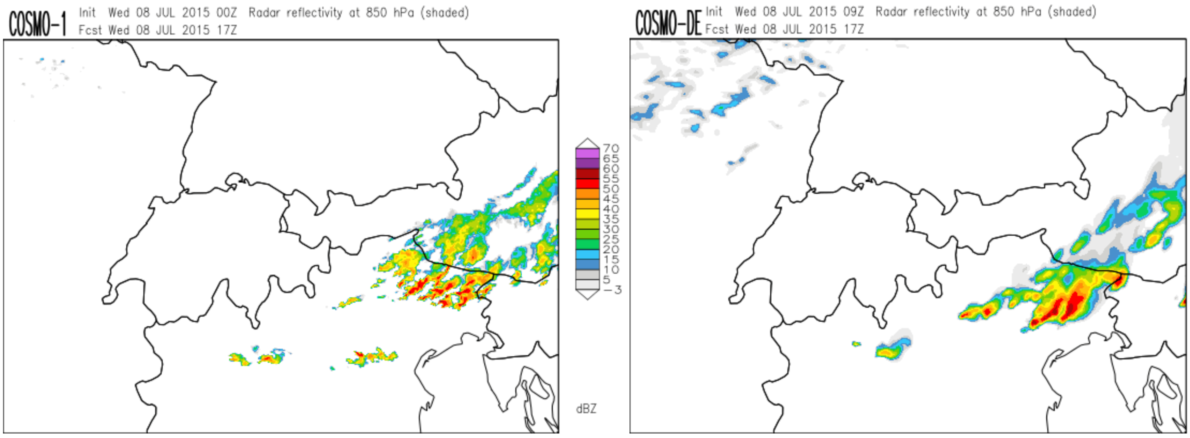

Figure 3.7.1: Two examples of deterministic high resolution and convection permitting NWP model output, prepared for the ESSL Testbed 2015. Left: COSMO-1 of MeteoSwiss (1.1 km horizontal mesh size). Right: COSMO-DE of DWD (2.8 km horizontal mesh size). In both cases the simulated radar reflectivity (dBZ) at the 850 hPa geopotential level (about 1500 m above sea level) is plotted. Geographical area shown is Switzerland and surroundings, black lines are national borders.

A one-dimensional hail growth model that can use both, NWP model soundings and observed soundings is the HAILCAST model. HAILCAST delivers objective, sound and skilful estimates of the maximum hail size (Jewell and Brimelow, 2009).

Ingredients Based Forecasting

Forecasts of hail do not need to rely exclusively on high-resolution (grid spacing on the order of 1-4 km) forecasts, but must also include coarser models that do not simulate individual storms, but parameterize them. From such models, quantities that may jointly be used as predictors for hail occurrence can be assessed. A climatological study of proximity soundings within RAIN, the largest study of its kind for Europe so far, (Púčik et al., 2015) has shown that the probability for large hail increased with increasing convective available potential energy (CAPE) and deep-layer wind shear (DLS, bulk shear). CAPE (a measure of instability and low level moisture) and DLS are parameters that can readily be diagnosed from NWP model output, which are three of four fundamental **ingredients** required for hailstorm formation. The CAPE represents the energy that the storm requires and the DLS the wind shear that causes it to become well-organized. The fourth ingredient is the presence of sufficient local upward flow, or lift, to initiate a storm. This ingredients-based method of forecasting convective storms was pioneered by Doswell (1987), Johns and Doswell (1992) and Doswell et al (1996). It is used in operational practice at the US Storm Prediction Center, experimentally at the European Storm Forecast Experiment (Brooks et al, 2011) and increasingly among weather services across Europe.

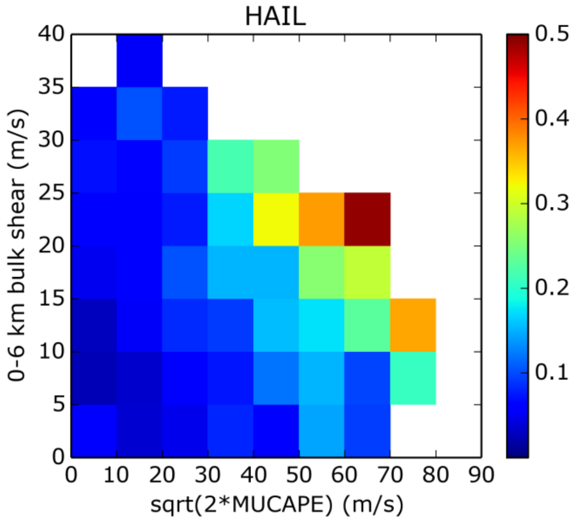

Figure 3.7.2: Probability of large hail in the MUCAPE/shear parameter space (Púčik et al., 2015)

Given that NWP models are currently able to forecast these environmental parameters but not hail itself, it follows that the role for the human forecaster remains essential. This role becomes especially important when some ingredients favour hailstorm formation, but one is missing, possibly because of a model error. As an example, a trained human forecaster will still forecast a non-zero probability of hail in an area that has no simulated precipitation according to the NWP model, if the parameters CAPE and DLS obtain high values that favour such storms. The ingredients based forecasting technique may not only be applied to NWP output (see figure 3.7.3) but also to observational in-situ and remote-sensing data such as radiosonde measurements. Therefore it can be applied to all time ranges as part of a continuous diagnosis by the forecaster, who will incorporate any new relevant data into its assessment as they become available.

Nowcasting

An exception to the statement given above, that forecasting large hail without a role of humans is currently not feasible, is in the field of Nowcasting. Nowcasting is a forecast in the 0 to 2 hour time range. In the Nowcasting range extrapolation techniques on the basis of already existing hailstorm cells can be applied mainly to weather radar data, assuming that a given system will continue to move in a particular direction and with constant speed. An advanced hail detection algorithm applied to the radar data is a prerequisite for an automatic hail Nowcasting technique. Use of polarimetric radar can in future help to better distinguish hail from other precipitation types.

Satellite meteorology offers microphysics products for Nowcasting. Such products can support hail detection.

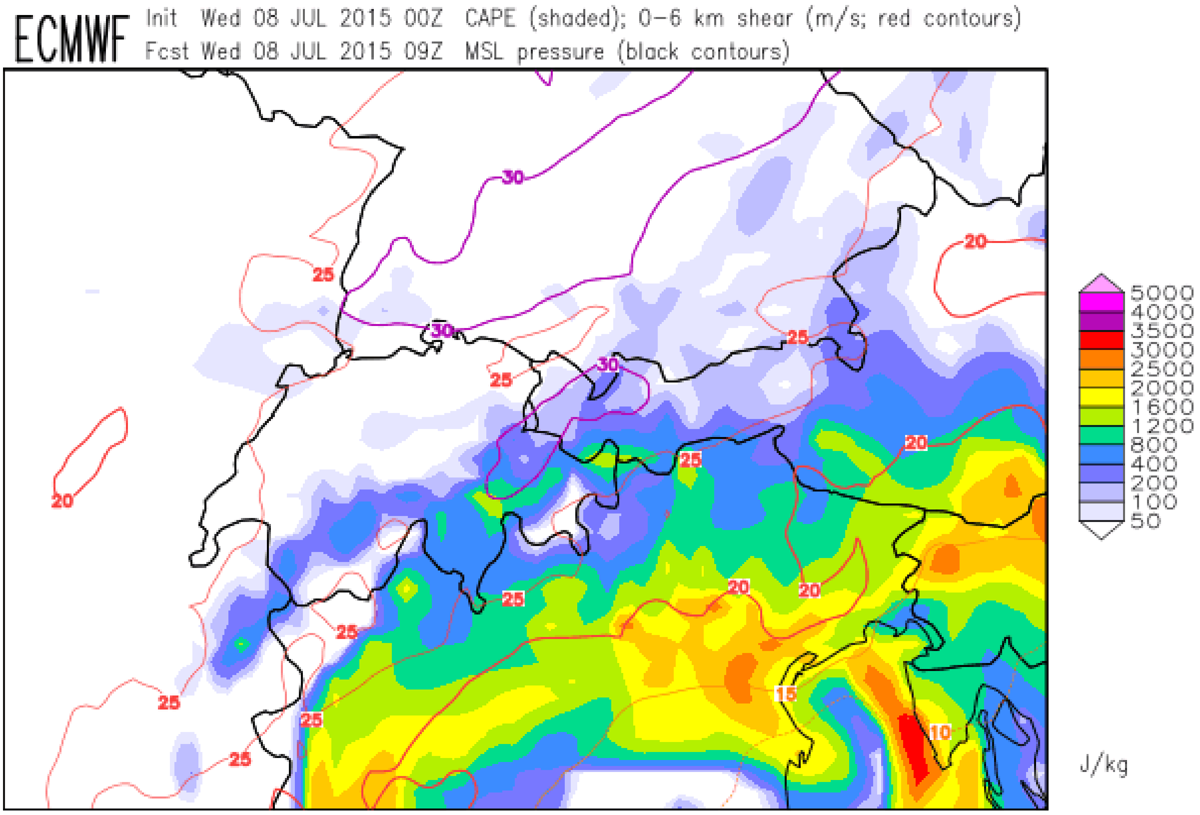

Figure 3.7.3: ESSL Testbed display of a weather map (data source: ECMWF) with three out of four ingredients for hail plotted in one weather map: moisture and instability (CAPE, J/kg, colour shaded), and DLS (m/s, isolines). Such weather maps are used for the ingredients based forecasting technique. Geographical area is Switzerland and surroundings, black lines denote national borders.

The success rates of all extrapolation techniques show a rapid decline over the 2 hour Nowcasting period. Not only the rapid life cycles of convective cells, their growth and their demise are sources of error, also the initiation of new cells and not least transformation of convective modes. The evolution of an unorganized cell into a rotating supercell, for example, causes important directional deviations from its previous track. This can be anticipated by a human forecaster in certain environments.

Automatic systems also try to take such deviations into account by the output of warning cones with wide opening angles, resulting in large geographical warning areas. Warning large areas with maximum lead times however easily causes an undesired high false alarm rate.

Regarding hail size estimates, a wider use of the earlier mentioned HAILCAST model could also be made in Nowcasting. HAILCAST appears to be the best tool presently available to forecast hail size (Jewell and Brimelow, 2009).

Results from interviews with weather services

54 % of the interviewed CI providers state that hail impacts their infrastructure (Groenemeijer et al., 2015). On the side of the weather services 10 out of 14 answered that they provide warning

products regarding hail at fixed daily times and 12 out of 14 weather services do so whenever necessary.

Table 3.7.1: Hail size (cm) as a threshold for the highest 3 warning levels used by weather services (letters A to G) in Europe. Comparison with an earlier study under the abbreviation "RauSch2008" (Rauhala and Schultz, 2008), "ESWD" reveals the thresholds of the European Severe Weather Database, "ESTOFEX" denotes the thresholds used by www.estofex.org, and "USA" gives the values used by the US National Weather Service at NOAA.

Weather Service	***Level 1***	***Level 2***	***Level 3***
A	0.6	2	
B	0.6	2	
C		2	4
D	any	2	5
E	1		
F	0.5		
G	any	2	
Mean	*0.7*	*2*	*4.5*
RauSch2008	*any – 2.5*	*1 - 2*	
ESWD		*2*	*5*
ESTOFEX		*2*	*5*
USA		*2.5*	*5*

A closer look reveals that most weather services do not distinguish between the rather frequent but low-impact events of small hail and the rare high-impact cases of large or extremely large hail. Only 5 out of 18 weather services warn specifically for hail sizes larger than 2 cm, only 2 out of 18 weather services warn specifically for hail sizes larger than 4 or 5 cm (see table below). Table 3.7.1 also lists the results of an earlier similar study, as well as the thresholds used for the European Severe Weather Database (Dotzek et al, 2009), in addition thresholds used by www.estofex.org, and thresholds used by the US National Weather Service.

While the ingredients based forecasting technique is used in the USA for many years, the lack of this forecasting approach in Europe until very recently may be a reason why few weather services are able to warn for large or extremely large hail - although these hail categories are responsible for the largest impact to CI. Another reason for the lack of such warnings may be that storm-based warnings in the Nowcasting range (opposed by warnings for larger areas) are still the exception in Europe.

In European warnings, hail is often included in severe thunderstorm warnings as one of the threats in a generic way, resulting in a relatively high percentage of weather services stating that they warn for hail. The distinction between thunderstorms with a small risk for hail and thunderstorms with a high risk for hail is not so prominently sought in Europe, even less the distinction between different hail sizes.

Warnings for extremely large hail are widely unavailable in Europe, independent of the warning time range. Regarding special products and warnings for CI customers, 5 out of 15 weather services answered that they issue such special CI products for hail, 4 do so for large hail – nearly a third. According to survey answers, main constraints on the side of the weather services are in general a lack of money for radar and forecaster training. A bigger role of EU funded projects in order to improve the forecasts is a wish of 92 % of the respondents, a very high percentage.

72 % of the weather services state that critical infrastructure operators should take both deterministic (yes-no-products) and probabilistic products into account for their decision making. Hail products that are issued for special CI sectors were not mentioned by the weather services in the RAIN survey.

Recently, a US product was presented which addresses the extended and long range forecasting time span and has shown some skill for forecasting severe convective storm environments out to a few weeks (Stepanek et al., 2015; Allen et al., 2015). The product is still in experimental mode. No such product is currently available in Europe. Hail forecasting products in Europe end at the 24-36 h early warning time, according to the RAIN survey results. Pistotnik et al (2014) presented first results of an effort to develop multi-year forecasts of severe storms, but these efforts are presently still thwarted by biases in climate models that need to be overcome.

3.7.3 Predictability

Unlike for large scale rain events, a yes-or-no forecast for hail and especially large hail will face enormous difficulties to balance out a good probability of detection with a low number of false alarms. Reasons are the small scale and the rare event nature of the phenomenon.

Point forecasts out to only about 30 minutes are useful in the deterministic sense, where manual and automatic extrapolation techniques can best be applied.

In the longer range, one can just forecast that the environment is conducive for hailstorms, but the precise location and timing of the event is literally impossible to forecast before the event actually unfolds. Therefore, for longer time ranges a probabilistic approach is used, when low absolute point probabilities would always lead to a negative yes-or-no forecast, but probability differences compared to the climatological background may be substantial.

Table 3.7.2: Availability of issued warning products. Source of WMO definitions: "DEFINITIONS OF METEOROLOGICAL FORECASTING RANGES"

Availability of warning products (issued products)	Hail						
Forecasting ranges according to WMO	0 – 2 h, Now-casting	2 – 12 h, Very Short Range Fore-casting	12 – 72 h, Short Range Fore-casting	72 – 240 h, Medium Range Forecasting	10 – 30 d, Extended Range Fore-casting	1 – 3 m, 3 Month Outlook, Long Range Fore-casting	3 m – 2 y, Seasonal Outlook (departure from climate values)
Public warning products at a given schedule	o	o	o	-	-	-	-
Public warning products and updates issued at any time necessary (24 h continuous monitoring)	o	o	o	-	-	-	-
Tailored warning products for CI customers at a given schedule	o	o	?	-	-	-	-
Tailored warning products and updates for CI customers issued at any time necessary (24 h continuous monitoring)	o	o	?	-	-	-	-
Communication with CI customers on a case by case basis (no fixed agreement)	o	o	o	-	-	-	-
Routine general forecasts (no products for extreme weather events)	o	+	+	?	-	-	-

Availability categories:

-	Not available.
o	Available from some weather services in Europe.
+	Available from many weather services in Europe (standard product).
?	Unknown.

The following example for such a situation shall illustrate this. It is freely assumed here that some added probabilistic value is available out to about 2 months, and, indeed, recent work (Stepanek et al., 2015) shows that NWP information out to about 2 months could be available in future. The example means that for a 1 to 3 month outlook the probability is twice as high as in the climatological mean, for the 10 to 30 days extended range the probability is already five times higher as in climatology, and finally in Nowcasting more than 150 times higher as in climatology. This output demonstrates a potential drastic difference and can deliver substantial added value for decision makers in the CI sector. Please note that even for the Nowcasting range (where the confidence and probability are highest in this point forecast) a deterministic forecast (a yes or no forecast) still would call for no large hail (because the probability is below 50 %), although the probability for large hail in this case is now more than 150 times higher on the given day than can be expected from climatology.

Table 3.7.3: Synthetic probability example for large hail (>2 cm) at a given point for different early warning times

Forecasting ranges according to WMO	0 – 2 h, Now-casting	2 – 12 h, Very Short Range Fore-casting	12 – 72 h, Short Range Fore-casting	72 – 240 h, Medium Range Forecasting	10 – 30 d, Extended Range Fore-casting	1 – 3 m, 3 Month Outlook, Long Range Fore-casting	3 m – 2 y, Seasonal Outlook (departure from climate values)
Point forecast probability in % for a given day in summer	47	22	17	8	1.5	0.6	0.3
Climatological probability in % for a given day in summer	0.3	0.3	0.3	0.3	0.3	0.3	0.3

Predictability as a function of vertical wind shear (VWS)

Organized forms of convection still come together with a relatively high predictability compared to unorganized convection in an environment of low VWS. Both, human forecasters and automatic systems extremely struggle in such low VWS situations, when newly formed cells seemingly behave chaotic, only some of them become severe, mere for a very brief period. These challenges result in a typical warning lead time close to 0 minutes for hailstorms in an environment with low VWS, given that there is some time needed to collect, process and disseminate the remote sensing signals (like from the weather radar), and that such convective systems often do not clearly move, but discharge their hail load where they originated. The added value of warning information is very limited saying that it might hail at a given place, when hail is already falling there.

For this reason in the USA at the National Weather Service forecasters only focus on storms in environments with at least moderate VWS. Per cell probabilities of becoming severe are much higher in conditions of noticeable VWS, and also predictability and lead time are much better.

Table 3.7.4: Skill of issued warning product. Skill categories:

Typical **Skill** of warning products (issued products)	Hail						
Forecasting ranges according to WMO	0 – 2 h, Now-casting	2 – 12 h, Very Short Range Fore-casting	12 – 72 h, Short Range Fore-casting	72 – 240 h, Medium Range Forecasting	10 – 30 d, Extended Range Fore-casting	1 – 3 m, 3 Month Outlook, Long Range Fore-casting	3 m – 2 y, Seasonal Outlook (departure from climate values)
Public warning products	o	o	o	-	-	-	-
Tailored warning products and updates for CI customers from land transport sector	o	?	?	-	-	-	-
Tailored warning products and updates for CI customers from energy sector	?	-	-	-	-	-	-
Tailored warning products and updates for CI customers from tele-communication sector	?	-	-	-	-	-	-

-	Products not available or useless.
o	Little use for some applications.
+	Useful, strong additional value compared to mean climate information.
?	Unknown.

3.7.5 Recommendations to improve the warning system

Based on the previous findings, we see the following potential for improvements:

1. Weather services should make wider use of the ingredients based forecasting technique. This will both help to extend the forecast range for large hail and improve Nowcasting and

very short range forecasting by means of a continuous diagnosis of the ingredients for large hail.

2. More efforts should be made to distinguish between small hail and large or even extremely large hail events. Warnings for (extremely) large hail are routinely available in the USA but not in Europe. Again, ingredients based forecasting would substantially help to prepare such warnings, as no direct NWP model output for hail is available. The HAILCAST one-dimensional maximum hail size model should be tested in Europe.
3. Newest generation high-resolution convection permitting model output can help the forecaster to predict the type of convective storm. Taking this information into account together with the background information from the ingredients based forecasting method can help to predict the probability of supercells and that of extremely large hail.
4. Intensive forecaster training and practice in the methods of ingredients based forecasting is required to improve hail forecasting. In particular, the benefits and caveats of using high-resolution convection permitting NWP model output need to be taught. A common caveat is a too literal interpretation of such model output. Both, deterministic and ensemble prediction system output of these models can lead the forecaster by its realistic appearance to the conclusion that severe hailstorms are not possible outside of areas with model precipitation. The larger the area of responsibility the more practice in forecasting severe storms there will be in a warning team. The European Storm Forecasting Experiment (www.estofex.org) demonstrates for many years now already that guidance on a European level is useful, and such guidance and second opinion provision is in fact desired by many European forecasting offices, especially from the smaller and medium sized ones who struggle to build their own know-how.
5. Based on the first promising attempt at NOAA also in Europe the prospects for long range outlooks should be assessed. Such outlooks could provide information about the probability for large hail events compared to climatological means.
6. Regarding verification, METEOALARM warnings should be centrally archived and this archive should be made available to the public, so that verification could be done by scientists and other interested stakeholders like CI customers.

3.7.6 Conclusions

As explicit warnings for large and for extremely large hail are not foreseen in many European weather services, large hail events are often treated as freak events on the edge of the possible forecasting spectrum.

Examples from the USA, from ESTOFEX and from the ESSL Testbed as well as from single weather services in Europe that do forecast extremely large hail demonstrate that such forecasts are in principle possible. This experience could stimulate more weather services in Europe to provide large hail warnings.

Guidance on a European level could help especially the small and medium sized weather services in their pre-warning forecast process.

For CI customers currently only very few weather services offer dedicated products to warn specifically for large hail, mainly in the form of automatic Nowcasting output for the time range up to 2 hours.

Probabilistic products would be needed to provide seamless warning information out to long range forecasts.

3.8 Thunderstorm gusts

3.8.1 Introduction

Damaging thunderstorm gusts can occur in a wide range of spatial and temporal scales, as well as in different environments and with different convective modes. One extreme would be dry microburst from rain showers evaporating in the dry air, affecting an area of perhaps only a few square kilometers. The opposite extreme would be a derecho (Gatzen et al., 2015), a convective windstorm that can produce damage swath covering hundreds of thousands square kilometers and that persists for many hours.

Correlated with the size of the convective system, with its degree of organization and its related longevity is the predictability of thunderstorm gusts.

The damage potential to CI rises with the gust strength and with the size of the affected area. Thunderstorm gusts pose a threat to all land based types of CI, interrupting rail and road based traffic, breaking power and communication lines, possibly causing cascading effects.

Straight line thunderstorm gusts in Europe are documented up to F3 strength (Pistotnik et al., 2011), corresponding to maximum gust speeds of 80 ±24 m/s, according to the "practical F-scale" used at ESSL (Holzer and Groenemeijer, 2015). In this case of 1st March 2008 as much as 12 pylons of 2 neighboring high voltage power lines were destroyed in Upper Austria close to the German border, causing a critical situation in the power grid of central Europe.

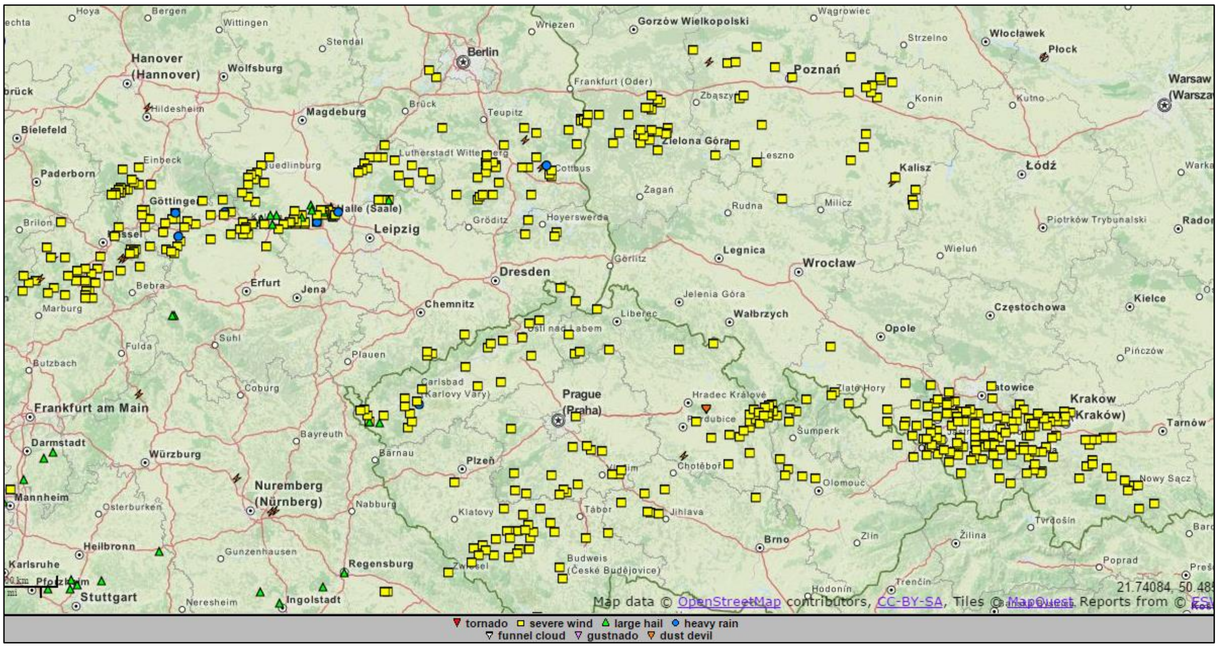

Figure 3.8.1: ESWD map of all severe weather reports of the 7th and early 8th July 2015 in a part of central Europe (eastern Germany, Czech Republic, northern Slovakia, southeastern Poland). Yellow squares denote hundreds of damaging thunderstorm gust reports.

Very recently, on the 7th of July and into the early morning hours of the 8th of July 2015 hundreds of reports of damaging thunderstorm gusts were received in the European Severe Weather Database (ESWD). Many of them reporting blocked roads, blocked railways, destroyed power and telecommunication lines - massively for example in the region close to Krakow in southern Poland (figure 3.8.1).

3.8.2 Assessment of warning systems

Numerical Weather Prediction

Development in NWP ever goes towards higher spatial and temporal resolution and also towards physical and convection-permitting model architectures. Explicit modelling of convection makes sense as the horizontal mesh size of operational nested models now approaches 1 km. Global models are still much coarser and need to parameterize convection on each grid point. Parameterized schemes do model convection less realistically and are not able to model physical interactions as well as convection-permitting ones. The latter are better able to reproduce cold-pool developments beneath convective storms and their interactions and role in the initiation of new convective cells. Therefore the representation of thunderstorm gusts in such models is becoming better.

High-resolution NWP models are able to simulate the situations with potential for severe wind gusts and their gust swaths, but often the timing and location do not correspond with reality. That means that even high-resolution ensembles are not able to catch convective storms in all spatial and temporal details or can even fail to produce a storm at all.

Nevertheless, state-of-the-art high resolution models are increasingly able to reproduce the correct type of convective mode. It means that such models can show the forecaster by the shape, intensity and coverage of the convective cells if for example short-lived unorganized cells are dominant, or better organized multicells, or linear convective systems, or even supercells. And the corresponding wind gust output gives an idea what can happen if the modelled scenario becomes real. An ensemble display of such model runs will show what the different results produce. Depending on the display type that can for example be a maximum projection of all ensemble outcomes (see figure 3.8.2).

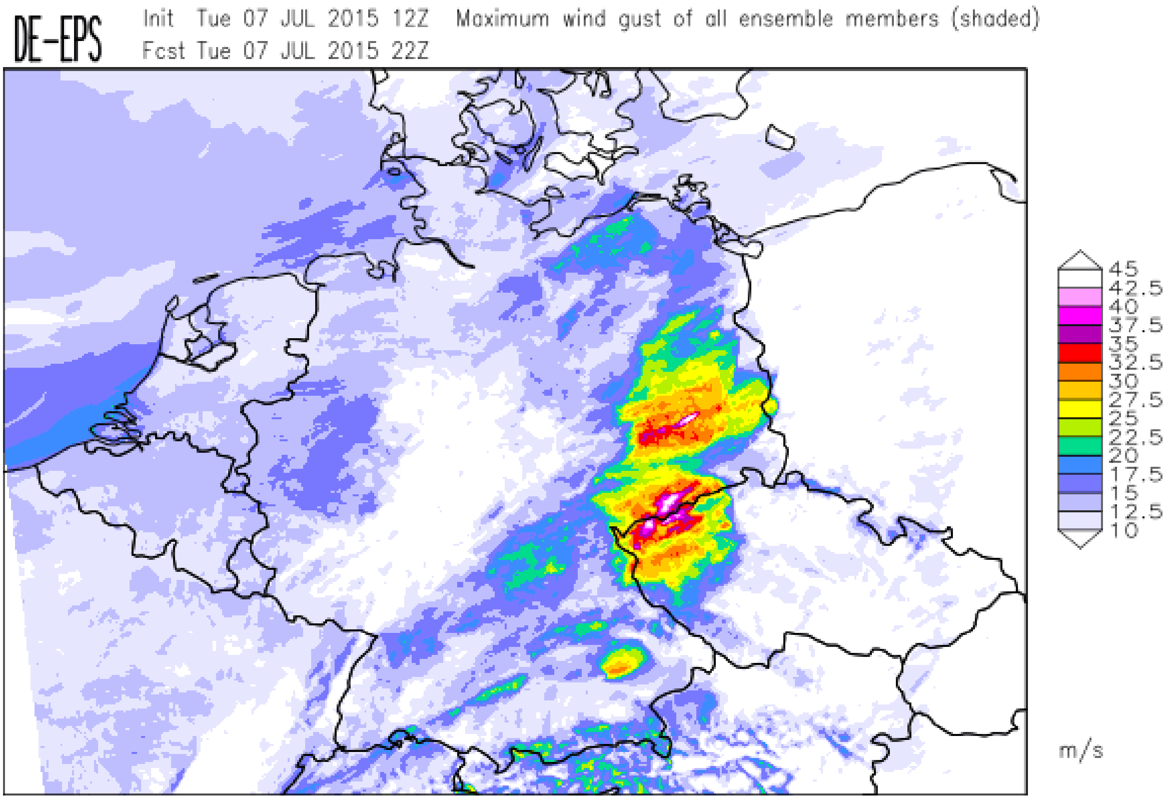

Figure 3.8.2: Maximum projection of all DE-EPS ensemble model runs (DWD): maximum wind gust forecasts (m/s) for the hour 7 July 2015, 21 to 22 UTC. Very high gust speeds up to 45 m/s are shown in the Czech-German border area and again further north in a smaller area of eastern Germany.

Ingredients Based Forecasting

High-resolution NWP models can in some cases produce astonishing forecasts and can be completely off in other cases. Global models with their coarser resolution currently are not able to explicitly model convection.

For both deficiencies the ingredients based forecasting technique offers strategies to overcome this problem, at least in a probabilistic sense. This is possible because models are often not able to exactly reproduce convective storms in their model world, but they are much better able to catch the atmospheric environment on a broader scale.

A very recent study within RAIN (Pucik et al., 2015) shows a bifurcated distribution of severe thunderstorm gust (see figure 3.8.3). One maximum, mainly based on wintertime events, is found in an environment of very high deep layer shear (DLS) but very low most unstable convective available energy (MUCAPE). The second and broader maximum, mainly based on summer season events, is found in an environment of both high DLS and high MUCAPE.

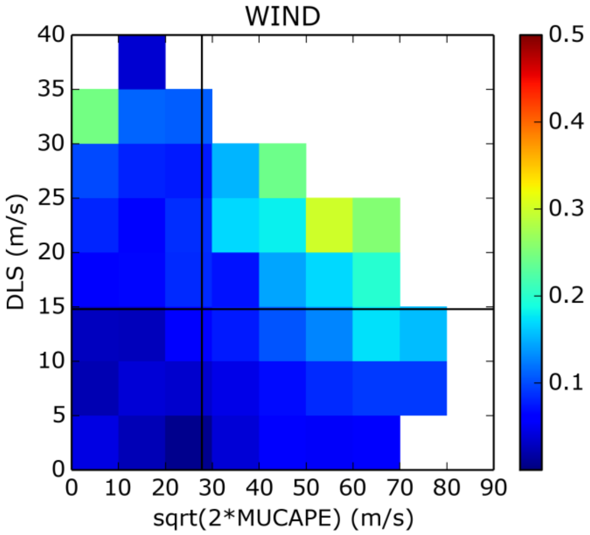

Figure 3.8.3: Probability of severe wind gusts in the deep layer shear (DLS) and most unstable convective available potential energy (MUCAPE) parameter space. Horizontal and vertical black lines represent mean values of MUCAPE and DLS (Pucik et al., 2015).

This result shows that in addition to the three basic ingredients for convective storms - moisture, instability (just a little needed in winter time) and lift – the ingredient shear plays a major role for thunderstorm gusts.

Difficult to forecast remain very small-scale downdraft events of “dry microbursts”, mainly driven by evaporative cooling of precipitation in a very dry low level air layer, and of “wet microbursts”, mainly driven by high precipitation load.

Nowcasting

Automatic Nowcasting of thunderstorm gusts can be made in different complexity. The most advanced automatic systems in Europe currently are the NowcastMix system of the German Weather Service DWD and the INCA system lead by the Austrian Weather Service ZAMG. Such systems make use of observational and NWP data from a variety of sources and blend them in different ways, for example with fuzzy logic.

In any way, automatic Nowcasting of thunderstorm gusts is difficult as long as there is no wind gust signal available from (automatic) surface observations. As long as such direct wind measurements are not available (for example because stations were not yet hit), generic wind gust estimates need to be assigned to proxy data (most often to weather radar signals and typically to their reflectivity data and not to their Doppler wind data). Such an indirect method based on the strength of the radar reflectivity signal leads to a high number of false alarms, because the relationship between high reflectivity and strong gusts alone is far from perfect.

Manual Nowcasting can add value to the automatic systems or go parallel in two ways:

- Human forecasters can directly extrapolate weather radar and/or satellite signals, and they can take into account the shape of such signatures. Bowing line segments (“bow echoes”, see figure 3.8.4) or “hook echoes” for example are known to be strongly related with severe gusts.
- Human forecasters can, by a continuous diagnosis of the ingredients for severe thunderstorm gusts, anticipate developments in an early stage and can hereby substantially increase the warning lead time (Beyer and Tuschy, 2015). Moreover this approach reduces the number of false alarms.

Prerequisite of a human forecaster Nowcasting approach is that the workload for forecasters in warning situations remains manageable. The size of the area of responsibility needs to be small enough to handle single storm developments on a busy day. Forecasters in addition need to be well trained and experienced.

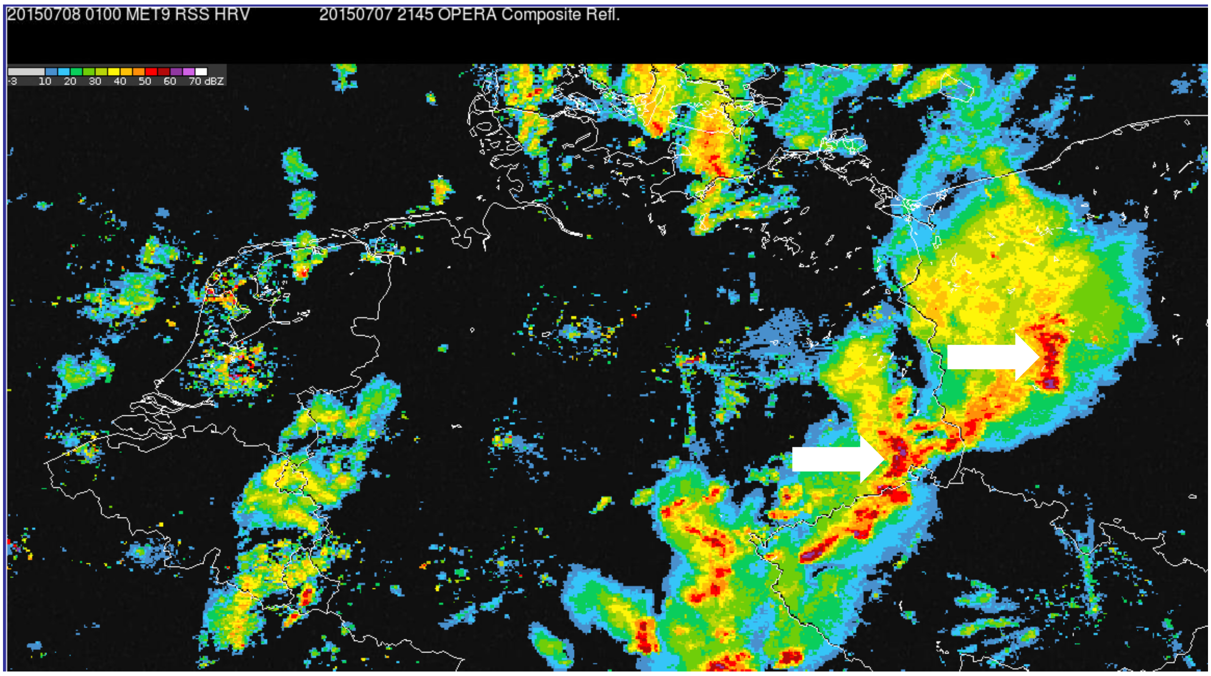

Figure 3.8.4: Bow echoes (marked by white arrows) associated with severe thunderstorm gusts, as seen on OPERA radar composite on late 7th July 2015 (source: OPERA via ZAMG).

3.8.3 Results from interviews with weather services

The RAIN report on “Past Cases of Extreme Weather Impact on Critical Infrastructure in Europe“ (Groenemeijer et al., 2015) states for CI damages caused by thunderstorm gusts: “As many thousands of households may be left without electricity as a result, the risk for a high societal impact exists.” In the same report the main measures mentioned on the side of CI managers are “arrangements with weather services for providing tailored warnings”. Such arrangements were made by 19 of 28 stakeholders (68%), and it becomes clear that for thunderstorm gusts a well-tuned warning system is required.

According to our RAIN survey data 14 out of the surveyed 18 weather services state that warnings for thunderstorm gusts are made whenever it is necessary, 10 weather services offer such warnings at fixed times.

Only 7 out of 18 weather services warn for extremely severe gust speeds of about 32 m/s, while some weather services have their highest warning threshold already reached by wind gust speeds of about 25 m/s (table 3.8.1).

These figures show that, albeit a bit less extreme, what has been observed for hail is also true for thunderstorm gust warnings. In a number of weather services in Europe no distinction is made between relatively frequent low impact and infrequent high-impact (extreme) events.

Table 3.8.1: Wind gust speeds (m/s) as a threshold for the highest 3 warning levels used by weather services (letters a to o). Comparison with an earlier study under the abbreviation “RauSch2008” (Rauhala and Schultz, 2008). “ESWD” reveals the thresholds of the European Severe Weather Database, “ESTOFEX” denotes the thresholds used by www.estofex.org, and “USA” gives the values used by the US National Weather Service at NOAA.

Weather Service	Level 1	Level 2	Level 3
a	20	28	42
b	21	25	30
c	20	25	33
d	18	25	31
e	15	20	
f	17		
g	15	28	33
h	20	25	30
i	18	23	29
j	24		
k	17		
l	15		
m	21	28	
n	15		
o	25		
Mean	*18.7*	*25.2*	*32.6*
RauSch2008	11 - 28	20 - 29	25 - 36
ESWD		25	
ESTOFEX		25	32
USA		25	(32)

Also other findings from the hail section relate to the findings for thunderstorm gusts:

Wind gusts are often included in thunderstorm warnings in a very generic way. The distinction between thunderstorms with a high risk for severe gusts and those without is often lacking.

The distinction between high and extreme wind gust speeds is only made by some weather services.

Only 3 out of 18 weather services issue manual specialized products related to thunderstorm gusts for CI customers, only 1 weather service issues an automatic specialized product.

Stakeholders in the RAIN survey mentioned that they wish to see the accuracy of the convective systems forecasts improved.

In addition it was required by the stakeholders that the severity of the event should be specified more accurately by media.

No CI sectors specialized products are issued for were mentioned in the RAIN survey answers.

Table 3.8.2: Availability of issued warning products. Source of WMO definitions: “DEFINITIONS OF METEOROLOGICAL FORECASTING RANGES”, retrieved on 30 March 2015: http://www.wmo.int/pages/prog/www/DPS/GDPS-Supplement5-AppI-4.html

Availability of warning products (issued products)	Thunderstorm gusts						
Forecasting ranges according to WMO	0 – 2 h, Now-casting	2 – 12 h, Very Short Range Fore-casting	12 – 72 h, Short Range Fore-casting	72 – 240 h, Medium Range Forecasting	10 – 30 d, Extended Range Fore-casting	1 – 3 m, 3 Month Outlook, Long Range Fore-casting	3 m – 2 y, Seasonal Outlook (departure from climate values)
Public warning products at a given schedule	o	o	o	-	-	-	-
Public warning products and updates issued at any time necessary (24 h continuous monitoring)	o	o	o	-	-	-	-
Tailored warning products for CI customers at a given schedule	o	o	?	-	-	-	-
Tailored warning products and updates for CI customers issued at any time necessary (24 h continuous monitoring)	o	o	?	-	-	-	-
Communication with CI customers on a case by case basis (no fixed agreement)	o	o	o	-	-	-	-
Routine general forecasts (no products for extreme weather events)	o	+	+	?	-	-	-

Availability categories:

-	Not available.
o	Available from some weather services in Europe.
+	Available from many weather services in Europe (standard product).
?	Unknown.

3.8.4 Predictability

The predictability of thunderstorm gusts is strongly related to the magnitude of vertical wind shear (VWS), as explained in the “Ingredients Based Forecasting” section above. VWS increases the degree of organization and thus also the strength and longevity of a convective system. “Bow echoes” and Supercells are examples of such well-organized convective systems, known to be high probability producers of severe gusts.

Based on the regional climatology, hook echoes associated with supercells or bow echoes associated with linear convective systems account for the majority of severe gust cases. For Germany a 15-year study of convective wind events (Gatzen, 2013) clearly demonstrates that long lived bow echoes are responsible for the vast majority of events. This study finds that the average number of severe wind gust reports per bow echo complex is 11.8, its average maximum gust speed is 35.4 m/s, the average path length is 350 km and the average duration 420 minutes.

In very prominent situations, ingredients based forecasting methodology can be used to forecast high risk of severe wind gust even days ahead. Approaching the forecasted event in time, the probabilistic forecasts will gain more and more confidence.

Deterministic forecasting of single thunderstorm gust events is mainly subject to Nowcasting and in some cases can be done out to the Very Short Range Forecasting (compare with Gatzen, 2013). Ensemble prediction systems of high-resolution convection-permitting models can be used to assess forecast probabilities further ahead in time, at most out to a few days - where such NWP systems are available.

As explained further above, very small scale microbursts (dry and wet ones) are extremely difficult to predict. Best predictions are expected when such events already have happened in a given situation somewhere and similar convective events are ongoing or further forecast. In such cases, supported by ingredients based insights, a forecaster can anticipate more microburst events in other places.

Table 3.8.3: Skill of issued warning products.

Typical **Skill** of warning products (issued products)	**Thunderstorm gusts**						
Forecasting ranges according to WMO	0 – 2 h, Now-casting	2 – 12 h, Very Short Range Fore-casting	12 – 72 h, Short Range Fore-casting	72 – 240 h, Medium Range Forecasting	10 – 30 d, Extended Range Fore-casting	1 – 3 m, 3 Month Outlook, Long Range Fore-casting	3 m – 2 y, Seasonal Outlook (departure from climate values)
Public warning products	+	+	o	?	-	-	-
Tailored warning products and updates for CI customers from land transport sector	+	+	?	?	-	-	-
Tailored warning products and updates for CI customers from energy sector	+	+	?	?	-	-	-
Tailored warning products and updates for CI customers from tele-communication sector	+	+	?	?	-	-	-

Skill categories:

-	Products not available or useless.
o	Little use for some applications.
+	Useful, strong additional value compared to mean climate information.
?	Unknown.

3.8.5 Recommendations to improve the warning system

We see a potential for improvements:

- The forecast range could be expanded further into the future if weather services would make wider use of the ingredients based forecasting technique.
- We encourage the further development of high-resolution convection-permitting ensemble prediction systems in order to retrieve more probabilistic forecast information.
- As the long-lasting bow echoes (Derechos) cause the majority of severe wind gust cases in the warm season in Germany as well as the most extreme gusts, the need of forecasting such events in western Europe is evident. In other regions of Europe other types of organized convection (like supercells) may play a bigger role.

- As extreme gusts well above 30 m/s lead to the worst impact on CI, it is important to distinguish between the more frequent events with gusts above 25 m/s from the extreme events with gusts above 32 m/s.
- Please refer to the last 4 items of the hail recommendations that do apply for thunderstorm gusts too.

3.8.6 Conclusions

Explicit warnings for extreme thunderstorm gusts are foreseen only by some European weather services. In order to cover those events with the highest impacts it is recommended to distinguish between high and extreme gusts, whenever possible.

As for hail it is also true for thunderstorm gusts that guidance on a European level could help especially the small and medium sized weather services in their pre-warning processes.

For CI customers currently only 4 out of 18 weather services offer specialized products related to thunderstorm gusts, although such events were in the past repeatedly responsible for high-end impact cases like multiple failures of high voltage power lines and long-lasting interruptions of road and rail networks, leading to cascading effects.

Probabilistic products are needed to provide seamless warning information starting from Nowcasting out to long range forecasts.

3.9 Tornadoes

3.9.1 Introduction

The highest wind speeds on earth are found in tornadoes. Until recently, little was known about their occurrence in Europe because of a lack of data collection and data exchange. Since 2006, such data are collected in the European Severe Weather Database (ESWD) in a consistent and sustained way (Dotzek et al, 2009).

Occurrence

A first climatology of tornadoes in Europe (Groenemeijer and Kühne, 2014) shows that the highest tornado density in ESWD occurs in western and central Europe, while noting that underreporting of tornadoes is likely in southern and eastern Europe and the risk may be comparable, if not higher locally, in these regions. This is supported by the notion that 7 of the most 10 deadly historical tornadoes occurred in southern and eastern Europe. Annually, 278 tornadoes occur over land on average while an additional 139 events are reported over water. 31 of those are strong (F2 or F3) tornadoes. Violent tornadoes (i.e. of F4 or F5 intensity) are much rarer and were relatively infrequent during the past 15 years compared to their frequency in the 20th century. They are expected to occur in Europe on average once every 4 to 5 years (Groenemeijer and Kühne, 2014).

Impacts

The impact of weak tornadoes (F0 and F1 intensity) is typically comparable to microbursts (small scale thunderstorm gusts, see section 3.8 of this report). Strong (F2 and F3), and violent (F4 and F5) tornadoes pose a high threat to any critical infrastructure in its path.

Table 3.9.1: Fujita scale of tornado intensity as used by ESSL with mean winds per class (Holzer and Groenemeijer, 2015).

F-class	Peak wind, mean of class (m/s)
F0	27
F1	41
F2	60
F3	80
F4	105
F5	130

European design wind speeds for many engineered objects and buildings lie between 45 and 50 m/s. Such speeds are exceeded in tornadoes of F2 intensity or higher (Table 3.9.1.). In addition to the direct wind impact on CI, indirect impact must be expected. Trees can be damaged or uprooted at much lower wind speeds, but at F3 intensity no tree species can withstand the wind (Hubrig, 2015), causing total destruction of tree stands and its related consequences for all kind of CI (trees falling on power and telecommunication lines, on streets and railway tracks).

The extremely high wind speeds above 100 m/s in violent tornadoes can cause severe damage even to structures with the highest resistance standards including atomic power plants and steel-reinforced concrete buildings. On the 8th of July 2015, a violent F4 tornado led to the collapse of a pylon of a high voltage power line in the region between Padova and Venice in northern Italy (Holzer et al., 2015).

An important contributor to damage in the higher F-classes is impact by debris. Massive and large parts of buildings, vehicles or any other kind of object are picked up by violent tornadoes and cause unpredictable damage where they hit.

3.9.2 Assessment of warning systems

Numerical Weather Prediction (NWP)

None of the currently available NWP models is able to directly simulate tornadoes. An indirect forecasting method based on NWP relies on a correct simulation of convective storm type (or convective mode) by high-resolution convection-permitting models. A proxy parameter for supercells, the storm type responsible for the majority of strong and violent tornadoes, is the updraft helicity that such models simulate.

Updraft helicity is the product of vertical vorticity (rotation) and upward speed. Rotating updrafts are a defining characteristic of supercells. Although supercells spawn all violent and most of strong tornadoes, a difficulty lies in the fact that only a small fraction of all supercells produce tornadoes. An even more fundamental limitation is that even state-of-the-art high-resolution NWP models do not consistently simulate convective storms in the correct region and at the correct time.

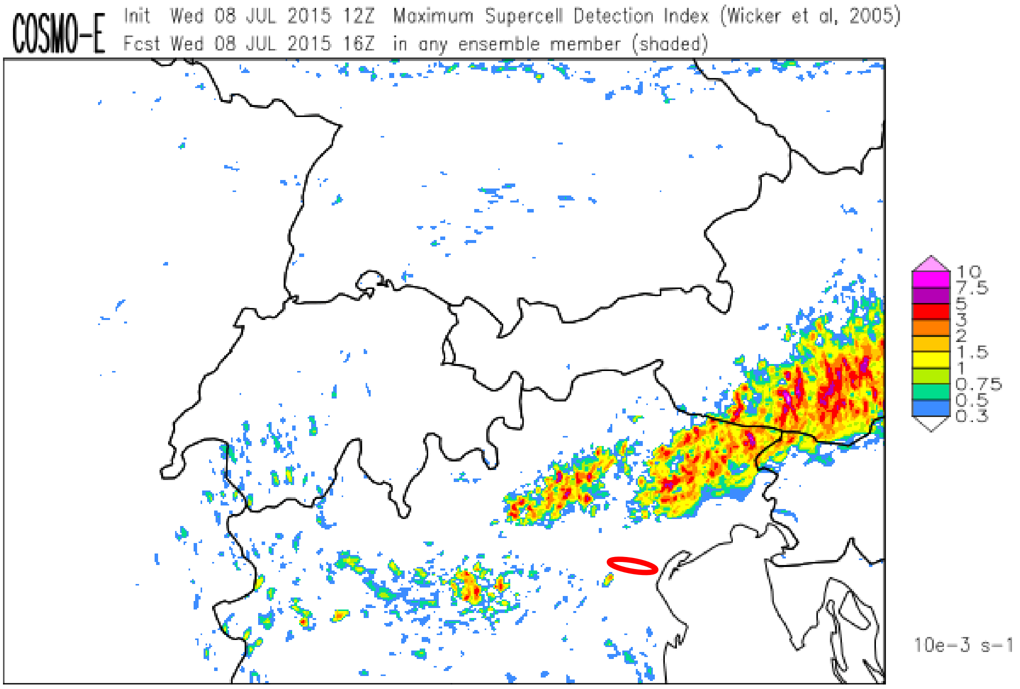

Figure 3.9.1: COSMO-E (MeteoSwiss) model ensemble display, maximum projection of supercell detection index (a way to grade updraft helicity) of all model runs. Red ellipse marks area where an intense and also large hail producing supercell spawned an F4 tornado between 15:25 and 15:45 UTC. This was a 4 hour forecast only, initialized at 12 UTC. The forecast would not have been available before the time of the event. Earlier runs on average show less true results.

An example that illustrates this is the storm that produced a violent F4 tornado on 8 July 2015 between Padova and Venice in northern Italy, which was not forecast by any of the ensemble members of the model (Figure 3.9.1). The model did correctly produce a number of intensely rotating storms further north and east as well as storms that affected the correct region in the evening (figure not shown).

To summarize, state-of-the-art high resolution models are increasingly able to reproduce the type of convective mode. It means that such models can show the forecaster if either short-lived unorganized cells, better organized multicells, linear convective systems or supercells are most likely to develop. Considering an ensemble of such simulations helps to assess how likely a particular scenario is, but it occurs on a regular basis that reality does not correspond to any of the simulations. In contrast to their parent storms, tornadoes themselves cannot be simulated operationally at this time because of their small dimensions.

Ingredients-Based Forecasting

For basic information about the ingredients-based forecasting technique we refer to sections 3.7 and 3.8 of this report. Tornadoes occur with convective storms. A first requirement for tornadoes to form is the presence of the ingredients needed for convective storms: instability, lift and moisture. Further analysis is required to find if conditions are not only favourable for convective storms, but also for tornadoes. Climatological proximity sounding data (Pucik et al., 2015) show that tornadoes occur in two sets of conditions, i.e. those favourable for tornadoes occurring with supercell storms and those favourable for non-supercell tornadoes. This results in different forecasting approaches for weak versus strong tornadoes.

While tornadoes in supercells require substantial CAPE and strong deep-layer wind shear DLS (reflected by the broad upper right maximum of tornado probability in Figure 3.9.2), non-supercellular tornadoes may occur with weak vertical wind shear. Such non-supercellular tornadoes can even be spawned beneath non-precipitating cumulus congestus clouds, if their updrafts stretch pre-existing near ground vorticity, for instance along shear zones of low level wind convergence lines. In such cases even multiple tornadoes can be initiated over land or water (waterspouts), the latter being the most common. This mode of tornado development is thought to be the reason for the small maximum in the lower left of Figure 3.9.2.

More importantly, potentially strong or violent supercellular tornadoes require strong vertical wind shear, especially in the lower troposphere. This may cause strong rotation in the thunderstorm (the so-called mesocyclone), which is a first step in tornado-genesis. Another importance factor is that the boundary layer should be moist, in order to reduce the strength of the storm downdrafts to allow downdraft vorticity pockets to stay near a strong updraft, which then results in a tornado.

Tornado-genesis is complex and is sensitive to numerous processes, but it can be summarized that strong vertical wind shear and a moist boundary layer are the most important forecasting ingredients to assess the tornado potential associated with supercells. These ingredients need to be continuously diagnosed during the whole forecasting and warning process. This needs to be done using NWP data many days in ahead of a possible event down to sub-hourly nowcasts, increasingly based on observational data.

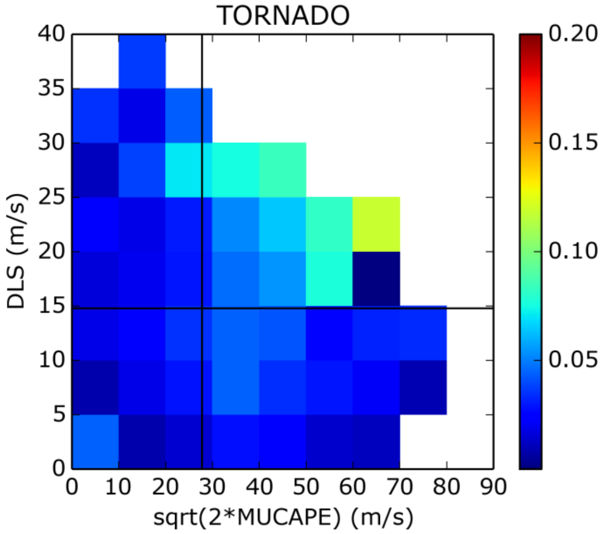

Figure 3.9.2: Probability of tornadoes in MUCAPE/DLS parameter space. Horizontal and vertical black lines represent mean values of MUCAPE and DLS (Pucik et al., 2015).

Nowcasting

Comprehensive tornado warning concepts in Europe have not yet been presented, published or implemented. In the USA, the final tornado warning is either based on very strong rotation detected by weather radars, visual reports of a tornado or a combination of both. Warning lead times are typically on the order of minutes, on average less than 20 minutes (Simmons, 2008; Koch, 2015). Strict warning dissemination procedures are in place, including media dissemination and preparedness actions.

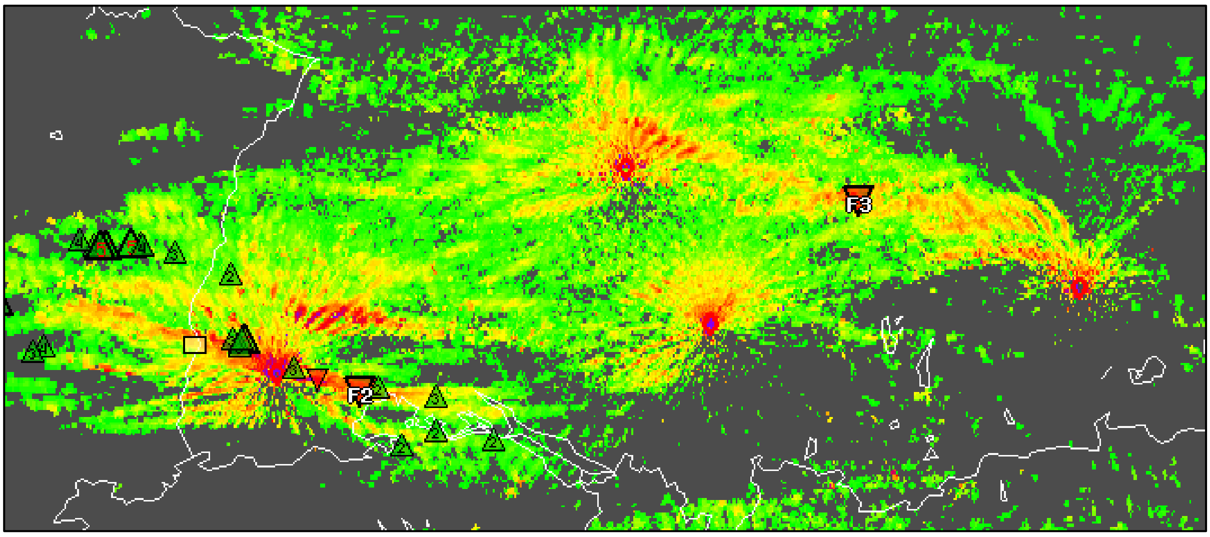

Figure 3.9.3: DWD experimental low-level rotation track product for the timeframe 19:00 to 21:00 on the 13th of May 2015 (colour shadings, strongest signal in reddish colour) for southwestern Germany (ESSL Testbed display). Overlay with symbols of severe weather reports from the ESWD (green triangles: large hail, yellow box: severe wind gust, red toppled triangle: tornadoes). Two tornadoes (including one F2) are associated with a long rotation track in southwest Germany, another F3 tornado near Augsburg is associated with a rotation track further to the northeast. Close to radar sites (red rings) high amplitude artefacts appear on the map.

Efforts to detect strong, potentially tornadic rotation from radar signals are currently being carried out at the German Weather Service DWD. Using the given radar network architecture, rotation signals are extracted with a so called mesocyclone detection algorithm (MDA; Wapler et al, 2015). This MDA and alternative rotation track products are designed to detect strong supercells, in other words strong parent storms of the smaller-scale tornadoes (Fig. 3.9.3).

The operation of weather radars is subject to the needs of different user groups, for instance hydrological users and air traffic control. Radars in Europe are typically not as well tuned for the type of Doppler wind retrievals required for the detection of tornadoes or their parent circulations as radars in the USA. Such high quality and high wind speed Doppler wind retrievals would be essential for the detection of strong rotation and for the successful detection of rotation on the spatial scale of the tornado itself.

In the near future, direct radar support for tornado warnings will probably remain unavailable for most warning forecasters in Europe. European warning forecasters need to rely on less ideal indirect methods only, as is the pattern recognition of hook echoes (that may form prominently in strong tornado cases).

Automatic Nowcasting techniques for tornado warnings are not yet operational and would need to rely on the relatively coarse MDAs and rotation signals. Such an experimental product was presented at the ESSL Testbed 2015: the radar rotation track product (see figure 3.9.3).

Results from interviews with weather services

In Europe, according to the RAIN weather service survey, most weather services do not warn for tornadoes (15 out of 18 do not warn), in line with earlier survey results by Rauhala and Schultz (2009).

A few weather services indicate that tornado warnings are foreseen, although clear warning strategies and warning concepts for tornadoes seem to be absent when it comes to the collection of ground reports, radar interpretation, the wording of the warnings as well as an efficient and time-saving communication strategy, given the very short lead time of only minutes.

RAIN survey data show that 2 out of 3 weather services that foresee the issuance of tornado warnings, want to do so 1 to 3 hours ahead of the expected event, but not closer in time to the expected event. Early warning times less than 60 minutes were only indicated by one weather service; early warning times of less than 30 or even less than 10 minutes were indicated by none of the weather services.

This poses the question what type of tornado warning these services want to put out. It can hardly be a storm-based warning of imminent tornado danger as it is done in the USA, but more a warning for a higher tornado probability. In that case, it remains unclear why such a product is not issued already much earlier, as the detection of ingredients required for tornado formation can based on NWP model data be already done up to days in advance.

Regarding specialized products for CI customers only one weather service (out of 18) offers tornado-related information to critical infrastructure service providers.

Table 3.9.2: Availability of issued warning products. Source of WMO definitions: "DEFINITIONS OF METEOROLOGICAL FORECASTING RANGES", retrieved on 30 March 2015: http://www.wmo.int/pages/prog/www/DPS/GDPS-Supplement5-AppI-4.html

Availability of warning products (issued products)	Tornadoes						
Forecasting ranges according to WMO	0 – 2 h, Now-casting	2 – 12 h, Very Short Range Fore-casting	12 – 72 h, Short Range Fore-casting	72 – 240 h, Medium Range Forecasting	10 – 30 d, Extended Range Fore-casting	1 – 3 m, 3 Month Outlook, Long Range Fore-casting	3 m – 2 y, Seasonal Outlook (departure from climate values)
Public warning products at a given schedule	?	?	-	-	-	-	-
Public warning products and updates issued at any time necessary (24 h continuous monitoring)	o	o	-	-	-	-	-
Tailored warning products for CI customers at a given schedule	-	-	-	-	-	-	-
Tailored warning products and updates for CI customers issued at any time necessary (24 h continuous monitoring)	?	?	-	-	-	-	-
Communication with CI customers on a case by case basis (no fixed agreement)	-	-	-	-	-	-	-
Routine general forecasts (no products for extreme weather events)	?	?	-	-	-	-	-

Availability categories:

-	Not available.
o	Available from some weather services in Europe.
+	Available from many weather services in Europe (standard product).
?	Unknown.

3.9.3 Predictability

An elevated (and still very low) probability for tornadoes can be indicated a few days in advance based on NWP model data, by addressing the necessary ingredients for tornadoes. Ingredients-based forecasting currently is also the only approach known to forecast a highly elevated probability for tornadoes in a seamless way, especially when it comes to short range forecasting, very short range forecasting and Nowcasting and is used, for instance, by the US Storm Prediction Center.

The time range defined as “Nowcasting” time-range, i.e. 0-2 hours, is far too long to put out storm-based warnings for tornadoes. Warnings based on ground reports or on Doppler wind radar signals are only possible with a maximum lead time of about 30 minutes. In the USA, which arguably has the most advanced tornado warning system globally, the average lead time is 13 minutes.

Regarding tornado probabilities (and forecast probabilities), it is required to define if such probabilities relate to directly being hit in a given location by a pre-defined maximum wind-speed (or F-scale class) of a tornado – a strict requirement or if such probabilities relate to a tornado that happens in a pre-defined spatial environment of a given location (or an area) – a less strict requirement. This distinction needs to be made, because tornadoes typically affect relatively small areas (about 8 km^2 in the case of the mentioned F4 tornado in northern Italy), and even smaller areas are affected by the maximum wind speeds (about 0.1 km^2 with F4 winds in the recent Italian case).

On a given day with a high-end forecast situation for tornadoes, for example in the Po-valley of northern Italy, the probability for a tornado within a radius of 40 km surrounding a verification point may be 10 %, while climatological values for the same day and area may be 0.01 %, i.e. a factor 1000 higher. Point probabilities are still orders of magnitudes smaller.

3.9.4 Warn-on-forecast

In the United States a programme called “Warn-on-forecast" (Stensrud et al., 2009) is being developed to combine nowcasting and very short range forecasting into a seamless prediction system. As part of this system, extremely high resolution NWP models with grid-spacing on the order of 100m assimilate radar data including Doppler wind data and simulate cell properties like cell rotation and motion. Very rapid model update cycles are required for “Warn-on-forecast”. The simulation is expected to cover a range of a few hours. By the application of “Warn-on-forecast” the gap between extrapolation and NWP-based methods shall be closed. This could in future increase the warning lead time for tornadoes. In order for this to work in Europe, high quality radar wind data that resolves the rotation in storm clouds must first become available.

Table 3.9.3: Skill of issued warning products.

Typical **Skill** of warning products (issued products)	Tornadoes						
Forecasting ranges according to WMO	0 – 2 h, Now-casting	2 – 12 h, Very Short Range Fore-casting	12 – 72 h, Short Range Fore-casting	72 – 240 h, Medium Range Forecasting	10 – 30 d, Extended Range Fore-casting	1 – 3 m, 3 Month Outlook, Long Range Fore-casting	3 m – 2 y, Seasonal Outlook (departure from climate values)
Public warning products	o	-	-	-	-	-	-
Tailored warning products and updates for CI customers from land transport sector	-	-	-	-	-	-	-
Tailored warning products and updates for CI customers from energy sector	-	-	-	-	-	-	-
Tailored warning products and updates for CI customers from tele-communication sector	-	-	-	-	-	-	-

Skill categories:

-	Products not available or useless.
o	Little use for some applications.
+	Useful, strong additional value compared to mean climate information.
?	Unknown.

3.9.5 Recommendations to improve the warning system

For most parts of Europe at present no tornado warnings at all can be expected. We therefore recommend to

- Initiate efforts to operationally monitor the risk of tornadoes on a European scale, together with other convective hazards
- Foster dissemination of proven tornado forecasting concepts through training activities. The main concept is that of performing a continuous diagnosis of the physical ingredients for

tornadoes using NWP and observational data, which has been proven itself in the Unites States.

- Develop comprehensive warning procedures for tornadoes, especially for regions with relatively high tornado frequencies, as these do not seem to be in place in Europe. Taking into account that the lead time is on the order of minutes, a fast and efficient warning concept is needed. Issuance of the warning as well as communication and media aspects need to be taken into account, accompanied by a preparedness programme. CI managers need to be included in both warning and preparedness programmes.
- Configure weather radars to allow detecting storm rotation, while not affecting the needs other radar stakeholder groups such as hydrologists and air traffic management more than necessary.
- Develop awareness campaigns about tornado risk and behavior in case of a tornado in the areas most at risk.

3.9.6 Conclusions

The fact that weather services do not warn for tornadoes, even in tornado prone and vulnerable regions of Europe, does not seem adequate. In most areas, tornado warnings are not available, neither as products tailored for CI managers, nor for the general public.

It is not a question if but rather when a major disaster will occur in Europe, and many lives could then have been saved by an appropriate tornado warning. Historical events caused dozens of fatalities - and this without touristic campsites or summer-time outdoor mass-events being present. In addition, high-speed trains or highly frequented roads are particularly at risk, but tornadoes have destroyed power and telecommunication infrastructure in the past. Such rare but high-impact events will not become significantly less likely in future and serious efforts are needed to overcome the current ignorance of this hazard, following the recommendations listed above.

4. Hazard independent survey results

4.1 Introduction

Many results from the RAIN weather service survey conducted in late 2014 were already presented in chapter 3 on a hazard by hazard basis. In this chapter we present additional and in general hazard independent survey results.

Explanation on the general setup of the survey is available at the beginning of chapter 3. The design outline of the questionnaire can be found in the Annex of this report.

4.2 Participating weather services and sample characteristics

The questionnaire for weather services was provided online. The invitation and request to take part in this online survey was sent out to 55 European weather services (national, regional and commercial/private ones) on the 30th of October 2014. All known weather services (based on the WMO list for national weather services and based on own internet search for other weather services) in Europe were contacted per email via direct contact points (where available) or the official email address. In a statistical sense the contacted sample was 100 %, a complete sample to our best knowledge. In addition a reminder was sent out to all contact points on the 24th of November 2014.

In total 18 weather services answered the online questionnaire until the end of 2014. Small weather services are over-represented in the answer sample. While the geographical distribution is balanced from west to east in the central and northern parts of Europe, southwest Europe and southeast Europe are under-represented. The following list indicates the names of the weather services that participated in the online survey (names as provided by the respondents, chronological order, 18 in total):

SMHI - Swedish Meteorological and Hydrological Institute
Latvian Environment, Geology and Meteorology Centre
MeteoNews AG
KNMI
MeteoLux / Administration de la navigation aérienne
Icelandic Meteorological Office
ZHMS of Montenegro
Lithuanian Hydrometeorological Service
Czech Hydrometeorological Institute
DWD Deutscher Wetterdienst
MeteoNetwork ONLUS
UBIMET GmbH
Slovak Hydrometeorological Institute
Danis Meteorological Institute
ZAMG
BLUE SKY Wetteranalysen
Geo-Meteo
Norwegian Met. Institute

13 of these weather services are national (or regional) [hydro-] meteorological services (NHMSs), 5 are commercial or private weather services. This answer sample is slightly over-representative for NHMSs given a ratio of 2.6 in the answer sample compared to a ratio of 1.8 for the complete sample.

4.3 Inventory of service provided

About half of the weather services provide tailored routine products for CI customers at a given schedule; public routine products are issued more often (Table 4.1).

Table 4.1: Identified services.

Identified services for extreme weather events	Positive responses out of 18 in total
Public routine products (forecasts or warnings) issued at a given schedule	15
Public routine products and updates issued at any time necessary	15
Tailored routine products for CI customers issued at a given schedule	7
Tailored routine products for CI customers issued at any time necessary	10
Information or communication with CI customers on a case by case basis, no fixed agreement	4
No products for extreme weather events issued, only routine general forecasts	2

Road management and power transmission are the RAIN CI categories most weather services (18 in total) provide specialized products for (Figure 4.1).

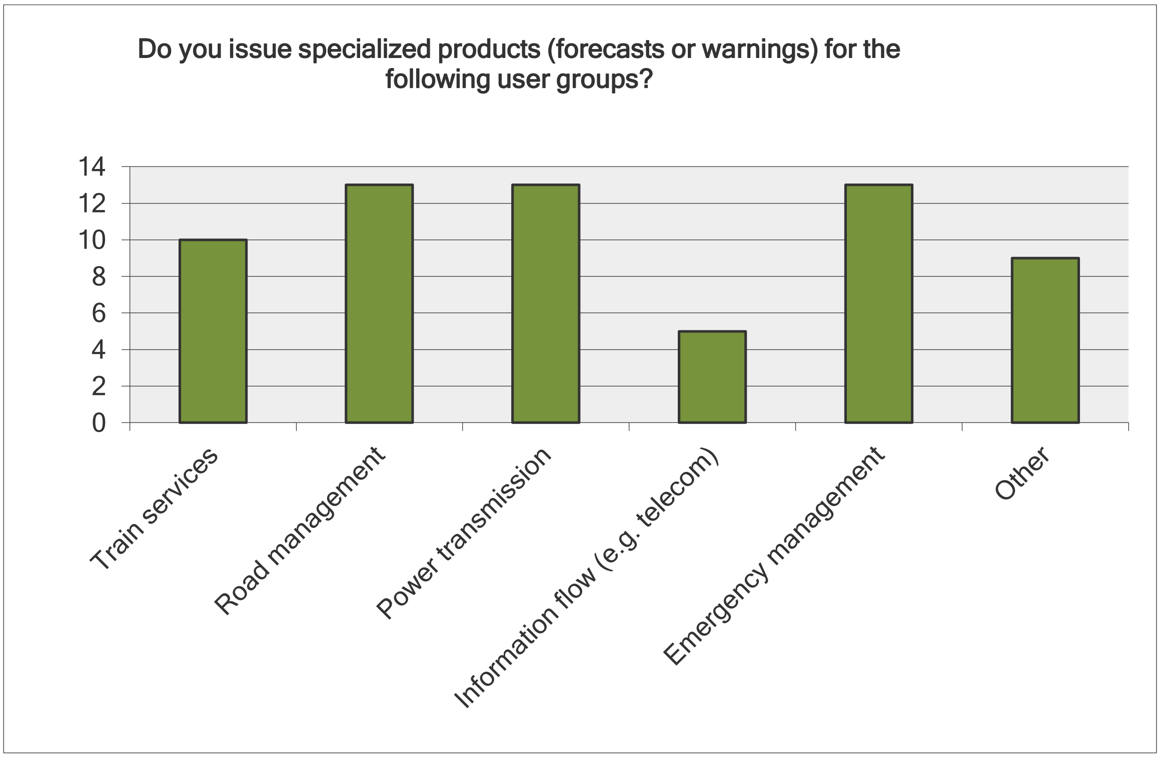

Figure 4.1: Specialized products issued.

Most weather services (13 out of 18) use fixed thresholds for their warnings for the whole country or area. Also other types of threshold definition are used, half of the weather services use impact-related thresholds (9 out of 18), see Figure 4.2.

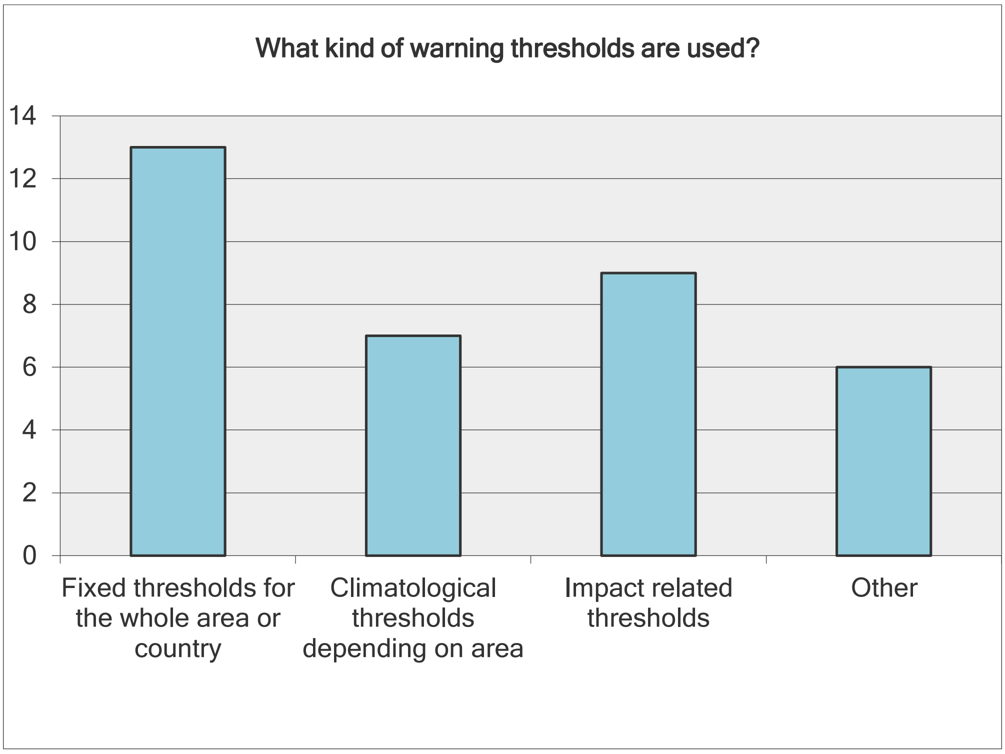

Figure 4.2: Type of warning thresholds.

4.4 Present arrangements

Parallel to the CI operators also the weather services were asked **what kind of essential framework arrangements they made with their CI customers** (Table 4.2). Most weather services closed contracts and deliver dedicated forecasts (13 out of 18).

Table 4.2: Nature of arrangements between weather services and CI operators.

Answer Options	Affirmative Responses (out of 18 in total)
Contract	13
Memorandum of Understanding	3
Detailed working procedures	6
Shared IT-systems	7
Dedicated forecasts	13
Involvement of weather service in emergency management	10
Other	1
No arrangements	2

Another result is that 6 out of 14 respondents answered that their arrangements are based on commercial agreements, 8 respondents state that they are based on non-commercial ones.

All weather services that answered the respective question (15 out of 18) stated that they tell the CI customer

- what skill to expect for a given forecast lead time, and
- what uncertainty can be expected in the forecast.

In addition, most weather services state that there are agreements about the reliability of the forecast.

All weather services (14 out of 18 answered this question) feel well informed about possible effects of extreme weather conditions on processes or assets of critical infrastructure customers.

12 out of 15 weather services measure the forecast quality on their side.

9 out of 15 issue probabilistic forecast products.

9 out of 14 exchange warning information with the neighbouring weather service.

4.5 Constraints

The RAIN questionnaire asked the weather services about different constraints and about the impact of national and EU regulations on their ability to offer warning products.

To the question

"***Are there any constitutional or legal constraints in the arrangements for weather forecasting?***"

11 out of 14 answered "no". One weather service that answered "yes" commented:

"For private weather services there are a lot of obstacles to get data access. Much cheaper data prices are available for close to government weather services. In some countries there is no possibility to get even essential data for the setup of special weather forecasts or warning systems."

To the question

"***Are there significant financial constraints on your side or on the side of your customers to close specific extreme weather arrangements?***"

3 out of 13 answered "yes". One weather service commented:

"Not enough money to set up AND RUN an appropriate radar network and/or (at least) greater automatic station network."

Nearly all respondents (12 out of 13) want to see a bigger role for EU funded projects to improve the forecasts (Figure 4.3).

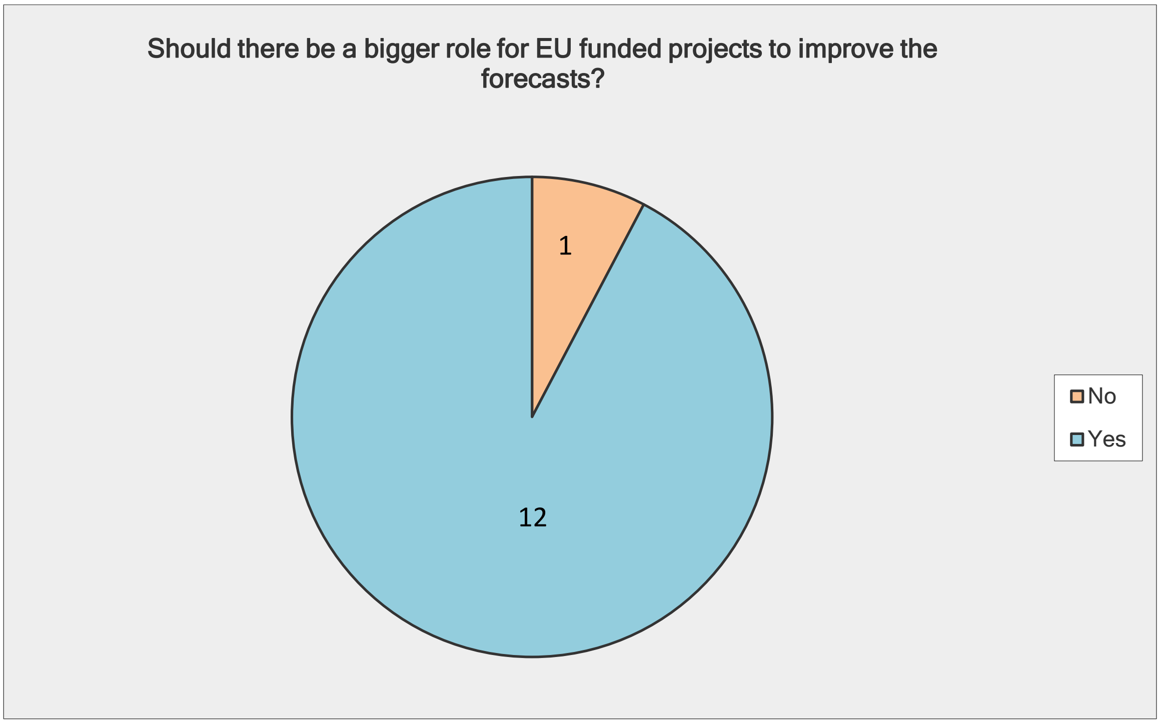

Figure 4.3: Role for EU funded projects.

5 out of 15 "feel that regional or national boundaries and data policies hinder (their) work". Comments:

"Even within the countries data is often administrated by regional entities and the data costs are highly variable at each region and country."

"Improvement needed for EU internal data exchange and cooperation, national services hinder European developments because of fearing negative influence on their business."

"The biggest obstruction of development of private meteorology is the national meteorological service."

"There is legal and political force to use certain meteorological providers in many EU countries."

6 out of 11 weather services are aware of "*warning quality issues in border regions*".

Not a single weather service feels "that EU policies or EU regulations hinder (their) work."

4.6 Suggestions for improvement

A number of weather services see room for improvements of warnings:

"Warnings should specify expected impact of dangerous phenomena".

"Amount of precipitation should be better forecast."

"There's no unique standard for warnings."

"Forecasts of flooding phenomena need improvement."

"The accuracy of the convective systems need improvement."

"We have limited access to national meteorological service's data although we pay taxes."

"Forecasts of severe storms need improvement."

"Severity should be specified more accurately by media."

"CAPE can be used more widespread."

"We do not have any communication with other meteorological companies and services."

Table 4.3.: Need for improvements. Per answer option one improvement category could be chosen. 8 weather services answered at least one of the answer options. Figures show how many weather services have chosen the respective improvement category.

What should be improved in the warnings and special weather forecasts given an optimal situation of resources?				
Answer Options	Improvement strongly needed	Improvement needed	Minor improvement needed	Forecast very good, no improvement needed
Features (content, event types, more precise forecast)	3	1	1	3
Accuracy	0	6	0	0
Timing	1	0	4	0
Interoperability (It means more common codes, comparable and common concepts and communication, joint and interconnected technical data. It means also common proceedings in conducting weather forecasts.)	2	3	0	1
User tailored warnings	1	1	3	0

Asked specifically, 3 out of 8 say that the interoperability needs to be improved, 2 out of 8 even see a strong need for such an improvement (Table 4.3), therefore a majority want's to see interoperability improved.

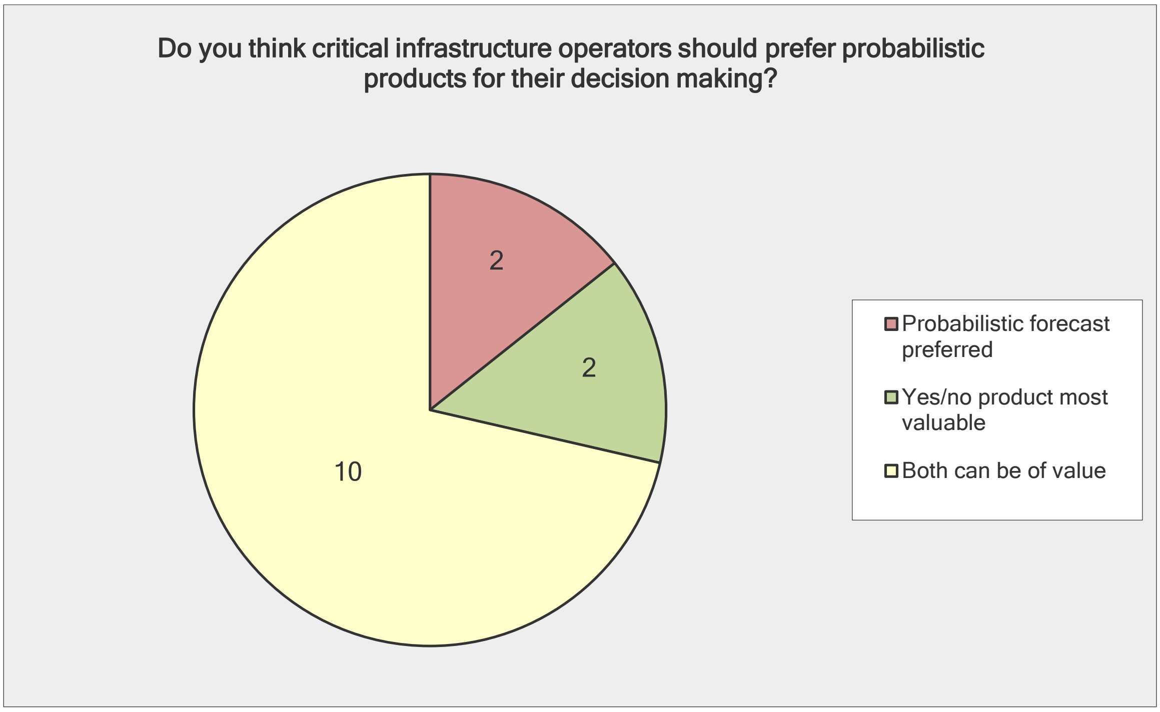

Figure 4.4: Deterministic or probabilistic product preference.

Only 2 (out of 14) think that CI operators should prefer probabilistic products, only 2 think the opposite, while the vast majority of 10 value both product types (Figure 4.4).

Finally we list the answers to the question

"***Could you suggest and describe the roadmap for improvements?***":

"The most important parts are not the forecasts and warnings, as these are already very good, but the improvement of the communication between the infrastructure undertaker and the meteorological data provider and the processes behind a certain forecast or warning. So the setup of checklists and decision support systems is essential for the organization of counter measures."

"Improvements should be on forecast accuracy, probabilistic forecast, user-friendly products."

"Our weather service is going to attend the Meteoalarm programme. In the future maybe not 2 but 3-5 days warnings will be issued on this web. We will implement the project and as a new step to the quality at operational work a (product name) workstation will start working."

"Our weather service is going to use Common Alerting Protocol during 2015. There will be better map products for nowcasting dangerous phenomena based on detailed objective analysis."

"Improvement can be achieved by use of model development in community, common / similar verification methods, more exchanges of verification results (models / alerts)."

4.7 Summary of hazard independent survey results

About half of the weather services provide tailored routine products for CI customers at a given schedule; public routine products in comparison are still issued more often.

Road management and power transmission are the RAIN CI categories most weather services provide specialized products for.

Most weather services use fixed thresholds for their warnings for the whole country or area. Also other types of threshold definition are used, half of the weather services use impact-related thresholds.

Most weather services closed contracts with CI operators and deliver dedicated forecasts. Non-commercial agreements slightly outbalance commercial ones.

Mainly private weather services suffer from limited data access and see legal constraints that hinder their work. Nearly all respondents want to see a bigger role for EU funded projects to improve the forecasts. The vast majority of weather services think that, both, probabilistic and deterministic product types are of importance for CI operators.

Important on the road to improvements is a better communication between weather services and CI operators. It was already an outcome of the previous RAIN task that CI operators regard communication with the weather service as very important. This relates to an easy flow of data, to also to direct contacts with human forecaster, who can deliver model output interpretation and scenario discussion. A similar result on the side of the weather services underlines the importance of the factor communication for a successful warning system.

5. Conclusions and recommendations

5.1 Assessment of state-of-the-art early warning systems

The assessment of warning systems in Europe leads to the insight that each of the different hazard types requires a very specific treatment. Not only are the modelling approaches very diverse, but also the availability and skill of different forecast and warning ranges differ greatly. The amount and type of effort that was put into developing modern warning systems differ substantially between hazards and from one country to another.

Table 5.1: Skill of issued warning products by European weather services, grade of best product category from Tables 3.1.3, 3.2.5, 3.3.7, 3.4.3, 3.5.4, 3.6.5, 3.7.4, 3.8.3 and 3.9.3 chosen.

Forecasting ranges according to WMO: Hazard type:	0–2 h, Nowcasting	2 – 12 h, Very Short Range Fore-casting	12 – 72 h, Short Range Fore-casting	72 – 240 h, Medium-Range Forecasting	10 – 30 d, Extended Range Fore-casting	1 – 3 m, 3 Month Outlook, Long Range Forecasting	3 m – 2 y, Seasonal Outlook (departure from climate values)
Windstorms	+	+	+	o	-	-	-
Heavy precipitation	+	+	+	o	-	-	-
Coastal floods	-	-	+	+	-	-	-
River floods	-	+	+	+	-	-	-
Heavy snowfall and blizzard	+	+	+	o	-	-	-
Wildfires/ forest fires	?	?	+	?	-	-	-
Hail	o	o	o	-	-	-	-
Thunderstorm gusts	+	+	o	?	-	-	-
Tornadoes	o	-	-	-	-	-	-

Legend:

-	Products not available or useless.
o	Little use for some applications.
+	Useful, strong additional value compared to mean climate information.
?	Unknown.

Table 5.1 reveals that the **skill of early warning systems** on ranges beyond 10 days is negligible for all hazard types (i.e. the forecast errors are too large), or that such products are not available at all. This is partly a consequence of the inherent limits to predictability of the weather at such time ranges, but also a signal that wherever research into forecasts on these time ranges takes place, they have yet to result into operational products that add value to climatological information.

On the short time scales up to 12 hours, warnings for windstorms, heavy precipitation, river floods and snowfall as well as for thunderstorm gusts have a good skill, although there are differences in quality from country to country. Flood warnings show useful skill out to 10 days, while wind storms, precipitation and snowfall can be predicted with less confidence at those timescales. Predictions for convective hazards have only limited skill after 12 hours. For time scales below 12 hours, warnings for thunderstorm gusts rate best, while state-of-the-art hail warnings show considerably less skill, tornado warnings the least.

The assessment of the state-of-the-art revealed that some countries have very advanced systems in place for some hazards, but that progress is slow in development in other countries and for other hazard types.

Pan-European programs and institutions such as Meteoalarm, the European Flood Awareness System, the nowcasting system INCA-CE, and the European Centre for Medium-range Weather Forecasts (ECWMF) are effective at mitigating these differences in warning system quality. However, they do only cover a part of the full spectrum of weather-related hazards and time ranges. Despite these and other projects, the **following problems** were identified:

- Limited forecast skill on short timescales and on timescales beyond 10 days.
- Strongly differing warning thresholds between countries (some even inverse to vulnerability considerations) and a lack of consideration of the relation between warning thresholds and potential impacts.
- Little international exchange of advanced weather forecasting methods, such as ingredients-based forecasting for convective hazards and forest fires.
- No continuous monitoring of the risk of convective hazards, forest fires or coastal floods on a European scale that would benefit countries.
- A hesitant adoption of probabilistic forecasts out of a fear that users will have difficulty to interpret them, which might be mitigated with further research in this area.
- Little pan-European cooperation to address rare very high-impact events such as coastal floods and tornadoes, which lend themselves to being addressed on a European scale.
- A lack of public availability of i) meteorological data, ii) warning products, and iii) warning verification data in reusable data formats from national weather services, ECWMF or EFAS, which would enable both researchers and the private sector to exploit such data and develop innovative warning products.
- Insufficient communication between weather services and CI operators that can lead to misinterpretation of warning products.

Table 5.2: Availability of issued warning products for CI customers (grade of best CI warning product category chosen from Tables 3.1.2, 3.2.4, 3.3.6, 3.4.2, 3.5.3, 3.6.4, 3.7.2, 3.8.2 and 3.9.2).

Forecasting ranges according to WMO: Hazard type:	0 – 2 h, Nowcasting	2 – 12 h, Very Short Range Forecasting	12 – 72 h, Short Range Fore-casting	72 – 240 h, Medium Range Forecasting	10 – 30 d, Extended Range Fore-casting	1 – 3 m, 3 Month Outlook, Long Range Fore-casting	3 m – 2 y, Seasonal Outlook (departure from climate values)
Windstorms	+	+	+	?	-	-	-
Heavy precipitation	+	+	+	o	-	-	-
Coastal floods	-	-	o	o	-	-	-
River floods	-	o	+	+	-	-	-
Heavy snowfall and blizzard	+	+	+	o	?	?	?
Wildfires/ forest fires	?	?	+	o	?	-	-
Hail	o	o	o	-	-	-	-
Thunderstorm gusts	o	o	o	-	-	-	-
Tornadoes	?	?	-	-	-	-	-

Legend:

-	Not available.
o	Available from some weather services in Europe.
+	Available from many weather services in Europe (standard product).
?	Unknown.

Besides the predictability aspect, this report also documents our findings for warning product **availability for critical infrastructure managers**, which is summarized in Table 5.2. It shows that windstorms, heavy precipitation events, river floods and heavy snowfall events are best covered by specialized CI products; tornadoes and coastal floods the least.

For the purpose of comparison with CI product availability, Table 5.3 lists the best warning **availability for public products**. In some cases, public warning products have a better availability than specialized CI products. For example, some weather services issue public products for windstorms in the time ranges from 10 days to 2 years, but none of the weather services is known to issue in addition specific windstorm products for CI operators. The same can be said for heavy precipitation and fires, while other hazards show no significant differences in availability between CI and public products. Needless to say public products are also available for CI operators, but not specifically tailored to their needs. To summarize, windstorms, heavy precipitation events, river floods, heavy snowfall and forest fires are best covered by public forecast products; coastal floods and tornadoes again the least.

Table 5.3: Availability of issued hazard-specific public warning products (grade of best public warning product category chosen from Tables 3.1.2, 3.2.4, 3.3.6, 3.4.2, 3.5.3, 3.6.4, 3.7.2, 3.8.2 and 3.9.2, general forecasts not included). Availability categories same as for Table 5.2.

Forecasting ranges according to WMO: Hazards:	0 – 2 h, Nowcasting	2 – 12 h, Very Short Range Forecasting	12 – 72 h, Short Range Forecasting	72 – 240 h, Medium Range Forecasting	10 – 30 d, Extended Range Forecasting	1 – 3 m, 3 Month Outlook, Long Range Forecasting	3 m – 2 y, Seasonal Outlook (departure from climate values)
Windstorms	+	+	+	o	o	o	o
Heavy precipitation	+	+	+	o	o	o	o
Coastal floods	-	-	o	o	-	-	-
River floods	-	o	+	+	-	-	-
Heavy snowfall and blizzard	+	+	+	o	?	?	?
Wildfires/ Forest fires	+	+	+	+	o	o	o
Hail	o	o	o	?	-	-	-
Thunderstorm gusts	o	o	o	-	-	-	-
Tornadoes	o	o	-	-	-	-	-

A comparison of Tables 5.2 and 5.3 (both availability) with Table 5.1 (skill, a measure of forecast error) shows that for some time ranges products are operationally made available that according to our assessment have little or no skill. This is true for nearly all hazard types and especially for public products (Table 5.3). In other words: Useless products are made available. This is most apparent for windstorms, heavy precipitation and fires, where products are made available even for seasonal outlooks (the forecast range from 3 months to 2 years), but forecast skill for these hazard types is only acceptable out to about 10 days.

On the other hand, for some hazard types, useful forecast skill is present, but few or even no early warning products are issued. This is the case for river floods and thunderstorm gusts in the very short range forecasting (2 to 12 hours). For hail and tornadoes it was shown earlier that useful skill is available in the very beginning of the Nowcasting range (only on the order of minutes), but no targeted warnings are available that make use of this small early warning time window.

5.2 Recommendations

In this section we give a number of recommendations as well as a number of recommendations specifically addressed to improve the warnings for a particular hazard. The recommendations for specific hazards is not exhaustive, and the reader is kindly referred to review the respective Section in Chapter 3 and its recommendations section to find the full list of recommendations.

General recommendations to the EU:

i) Develop European efforts to operationally monitor and study hazards that, because of their rare occurrence and complex nature, are best addressed at this scale. Such hazards are convective hazards (hail, flash floods, wind, and tornadoes), forest fires and coastal floods.
ii) Foster international research, collaboration and coordination involving weather services around Europe on a number of early warning-related issues, in particular:
   a. the relation between weather warnings and impacts
   b. the basis of determining warning thresholds
   c. the exchange of knowledge on best practices and innovations in weather warning methods
   d. research on the uses of probabilistic warnings
   e. improving forecast skill on timescales up to 12 hours (nowcasting and short-range forecasting)
   f. improving forecast skill beyond 10 days
iii) Require national and international institutions and programs to make meteorological data, warning data and warning verification data publicly available, in order to foster innovation by the academic and the private sector

The following listing highlights focus points for the individual hazards.

Windstorms:

- Facilitate the availability of condensed ensemble forecasts for warning forecasters.
- Adjust warning thresholds with respect to certain return periods in order to avoid large differences in warning frequencies of neighboring countries.

Heavy Precipitation:

- Installation of additional meteorological/hydrological stations and extension of the radar network, both preferably in regions with little or no data.
- Extend the focus from large-scale precipitation events with high accumulation levels to small-scale convective events with high intensities.

Coastal Floods:

- Create a pan-European warning system similar to the one existing for river floods.
- Extend the range of warnings by introducing Nowcasting and long-range forecast systems.

River Floods:

- Disseminate the EFAS forecasts and warnings directly to the public instead of routing them only through national agencies. This would also make such products immediately available to CI operators.
- Combine river discharge predictions with flood hazard maps.

Heavy Snowfall and Blizzard:

- Strengthen impact-related forecasting including more implications and explanations to CI operators.
- Make wider use of road weather forecasting systems.

Wildfires (forest fires):

- Continuously verify and adjust the forest fire indices.
- Take the type of vegetation into account in future warning systems and offer warnings via METEOALARM.

Hail:

- Make wider use of the ingredients based forecasting technique in order to expand the forecast range for hail and improve Nowcasting and very short range forecasting.
- Distinguish in warnings between small hail and large or even extremely large hail. Goal should be to warn for high-impact events different that for more usual events.

Thunderstorm Gusts:

- Further develop high-resolution convection-permitting ensemble prediction systems in order to retrieve more probabilistic forecast information.
- Use the ingredients-based forecasting technique and radar pattern recognition to better distinguish between extreme gusts well above 30 m/s and the related high impact for CI and the more frequent small-scale events.

Tornadoes:

- Set up, train and evaluate comprehensive warning procedures in order to overcome the current widespread lack of tornado warnings.
- Improve the weather radar system architecture and find a better balance between the needs for severe storms warnings and other user groups. This would be the very basis for storm-based warnings.

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Appendix: Weather Service Questionnaire Design

The following questionnaire was used online to conduct the RAIN weather service survey.

Paragraphs	Issue	Aspects	Elements to consider	Answers
1. Organisation	A. Interviewee	• Organisation • Name of the interviewee • Function/role		
	B. Type of organisation	• Public (national or regional [hydro-] meteorological service • Commercial or private weather service		
2. Inventory of service provided	A. Identified services for extreme weather events	• Public routine products (forecasts or warnings) issued at a given schedule • Public routine products and updates issued at any time necessary • Tailored routine products for CI customers issued at a given schedule • Tailored routine products for CI customers issued at any time necessary • Information or communication with CI customers on a case by case basis, no fixed agreement • No products for extreme weather events issued, only routine general forecasts • Other services, please specify.		

Paragraphs	Issue	Aspects	Elements to consider	Answers
	B. Identified functions that can be affected by extreme weather events with specialized products (forecasts or warnings) issued for	• Flow of road traffic • Train services • Power transmission • Information flow • Emergency management • Other, please specify.		
	C. Identified extreme weather events that are covered by specialized products (forecasts or warnings)		• Wind storms • Heavy rainfall • Coastal floods • River floods • Landslides • Tornadoes • Large hail • Thunderstorm gusts • Lightning • Snow (storms) • Freezing Rain and Icing • Wildfires • Heat or cold waves • Dense fog • Other?	
	D. What kind of thresholds are used?	• Fixed thresholds for the whole area or country? Climatological ones? Other?		
	E. Inventory of product (special forecast or warning) thresholds for covered extreme weather events			

Paragraphs	Issue	Aspects	Elements to consider	Answers
3. Present arrangements	A. What kind of (essential framework) arrangements are made between CI customers and your weather service?		• Contract? • MoU? • Detailed working procedures? • Shared IT-systems? • Dedicated forecasts? • Involvement of weather service in emergency management? • If no: go to question 4	
	B. Are they based on commercial or non-commercial agreements?			
	C. For which types of extreme weather events?		• All types of events? • If no: for which events?	
	D. Information exchange is done by?		• Telephone • IT-system • Mails • Other?	
	E. How specialized in time and space are the warnings for extreme weather events of different size and duration?	• E.g.: Long lasting freezing rain versus short lived thunderstorm.	• If so why? • Different agreements for different extreme weather events?	
	F. What kind of early warning time is used for the identified extreme weather events? Are there fixed lead times for different weather events?		• Hours • Day • Several days	• Answer for every event category.

Paragraphs	Issue	Aspects	Elements to consider	Answers
	G. Did you tell the CI customer what skill to expect for a given forecast lead time? Is the forecast uncertainty specified?		• Are there agreements about the reliability, so the shorter the expected major event will arise the better the forecast will be (or in other words: the shorter the lead time, the better the accuracy)?	
	H. Are you informed about possible effects of extreme weather conditions on processes or assets?			
	I. Is the quality of the forecast measured on your side?			
	J. Do you issue probabilistic forecasts?			
	K. Do you issue automatic and/or manual products?		• Manual or auto-warn products, e.g. for SMS Warnings? • Manual or automatic warnings for special customers?	
	L. Do you exchange relevant warning information with your neighbouring weather service?		• If yes, by which means?	
4. Constraints	A. Are there any constitutional or legal constraints in the arrangements for weather forecasting?			
	B. Are there significant financial constraints on your side or on the side of your customers to close specific extreme weather arrangements?			
	C. Should there be a bigger role for EU funded projects to improve the forecasts?			
	D. Do you feel that regional or national boundaries and data policies hinder your work?			
	E. Do you feel that cooperation agreements or legal constraints hinder your work?			
	F. Do you feel that EU policies or EU regulations hinder your work?			

Paragraphs	Issue	Aspects	Elements to consider	Answers
5. Suggestions for Improvement	A. What should be improved in the warnings and special weather forecasts, given an optimum situation of resources?	• Interoperability (It means more common codes, comparable and common concepts and communication, joint and interconnected technical data. It means also common proceedings in conducting weather forecasts.) • Border crossing issues: what about possibilities and quality of warnings near borders? • Do you see an improvement since the start of the meteoalarm project (www.meteoalarm.eu) of EUMETNET, compared to the situation before?? • If yes, what did improve with meteoalarm?	• Features (content, event types, more precise forecast) • Accuracy • Timing • Interoperability • User tailored warnings	
	B. Is a probabilistic forecast or a yes/no product most valuable for CI decision making?			
	C. Could you suggest and describe the roadmap for improvements?		• Plans?	