VTT WORKING PAPERS 168

Extreme weather impacts on transport systems

EWENT Project Deliverable D1

ISBN 978-951-38-7509-1 (URL: http://www.vtt.fi/publications/index.jsp)
ISSN 1459-7683 (URL: http://www.vtt.fi/publications/index.jsp)

JULKAISIJA – UTGIVARE – PUBLISHER

VTT, Vuorimiehentie 5, PL 1000, 02044 VTT
puh. vaihde 020 722 111, faksi 020 722 4374

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Series title, number and
report code of publication

VTT Working Papers 168
VTT-WORK-168

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Abstract

This report summarises the work done in 7 FP project EWENT, its first work package. D1 deliverable introduces a review of extreme weather phenomena and identifies their impacts and consequences on European transport system. All modes of transport are covered. Two main methods are used. First, there is an extensive literature review on extreme weather events and their impacts and consequences. Well over 150 scientific and professional references are studied and listed. This is followed by a review of media reported cases, almost 200 of them. With the help of these two methods and material they provide, critical threshold values for most relevant weather phenomena that affect different transport modes are listed. The phenomena have impacts and consequences which result in deterioration in the service level of transportation system. A dozen different impact mechanisms are charted and annexed to this report. Finally, brief summary of results is drawn, including a first-impression-discussion on strategic implications. Precipitation in all its forms (water, snow, hail) seems to dominate the harmful impacts. Road transport system seems to be the most vulnerable of modes.

ISBN
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Series title and ISSN VTT Working Papers 1459-7683 (URL: http://www.vtt.fi/publications/index.jsp)	Project number

Date April 2011	Language English	Pages 119 p. + app. 14 p.

Name of project	Commissioned by
Keywords Weather, transport, extreme weather	Publisher VTT Technical Research Centre of Finland P.O. Box 1000, FI-02044 VTT, Finland Phone internat. +358 20 722 4520 Fax +358 20 722 4374

Foreword

This project report gives what is probably the most extensive review to date on how extreme weather phenomena affect transport systems. Its value lies in its wide coverage. Far from being a fine-tuned publication, it is a robust selection of contributions from European transport and meteorological experts and researchers. These experts, the authors and editors, come from the following institutions: VTT Technical Research Centre of Finland, the German Aerospace Centre, the Finnish Meteorological Institute, the Austrian inland waterways operator *via donau*, the Cyprus Meteorological Service, the Institute of Transport Economics the European Severe Storms Laboratory.

Hence this is a unique combination of engineers, economists and meteorologists working together. Thus the work has not been easy, as different disciplines had to find common language and common methods of research. Undoubtedly many aspects have been left uncovered, and some areas are covered more in depth than others depending on available resources and expertise. However, this will serve as an effective springboard to the work to follow in the EWENT project, of which this deliverable is a part.

We hope that this report will also serve other purposes in addition to our project. Meteorologists need to understand what weather phenomena will have severe consequences on our mobility systems. Engineers need to understand how we can improve the resilience of the transport system and against what. Economists must make it clear what is doable in an economic manner. Policy makers must be ready to take appropriate steps. This report will help when starting to ponder these matters – it does not yet derive any significant conclusions and surely misses many details, but hopefully it will serve as a reference material when trying to find appropriate actions and strategies.

March 2011

Pekka Leviäkangas

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Appendices

Appendix A: Media database – an excerpt
Appendix B: Causal diagrams
Appendix C: Limits of Mediterranean forecast areas

1. Introduction

1.1 Scope and objectives

The EWENT project (Extreme Weather impacts on European Networks of Transport) funded by the European Commission under the 7th Framework Programme (Transport, Horizontal Activities) has the objective of assessing extreme weather impacts on the European transport system. EWENT will also monetise the assessed impacts and draft mitigation and adaptation strategies to make the transport system more resilient against extreme weather phenomena.

This Deliverable reports the findings of Work Package 1 (WP1) of the EWENT project. WP1 focuses particularly on identification and definition of extreme weather events within the European transport system context. The three tasks under WP1 were defined as follows:

– Task 1.1 Review of existing knowledge on extreme weather phenomena and impacts
– Task 1.2 Definition of criteria and ranking systems for the phenomena
– Task 1.3 Linking the key phenomena to transport system key parameters.

The results of the tasks are summarised in this report as follows: First, the introduction presents the scope, main terminology and method of research of the EWENT project. This is followed by a more general discussion on extreme weather and different aspects seen as relating to the term “extreme”. A description of the method of analysis is given next. Rather than relying on a single, identifiable methodology, the method is a process of applying a combination of several research methods.

Section three presents the literature and knowledge base for weather impacts on transport systems from four different perspectives, namely (1) literature per phenomena, (2) literature by transport mode, (3) media mining results and (4) selected case events. Fourth, we look at preliminary transport system performance indicators in the context of extreme weather. Threshold values for critical weather parameters are then discussed. In the final section, an example of a list of key weather parameters linked to transport system performance indicators is provided for use in the next research steps of the EWENT project.

There are two important annexes to this deliverable that are worth noting. The first is the media database in Appendix A. This database, still restricted for the consortium, will be utilized throughout the project. It consists of almost 200 cases of identified extreme weather events with significant impacts on transport systems, and covers multiple countries. The second is the causal diagrams in Appendix B. They describe the impact mechanisms from weather phenomena to consequences and transport system performance indicators. The diagram list may not yet be exhaustive, but can be completed by the end of the EWENT project, if the need arises.

1.2 Phenomena, impacts and consequences in the EWENT context

The causal relationships between extreme weather and transport system performance require building a chain of relationships and defining contextual terminology. The basic terms are phenomena, impacts and consequences. It is clear that the borderlines between these concepts and their contents are not absolute, but rather flexible and they are often used inconsistently.

In the context of EWENT and this Deliverable, *weather phenomenon* simply means the kind of weather we are addressing. The phenomenon intensity and severity is then measured by weather parameters expressed in SI units (e.g. mm / 24 h) or meteorological units (e.g. Fujita or Beaufort scale). For most, SI units are used. Between phenomenon and impact of the phenomenon there is the direct causal result, physical in nature, such as that depicted in Figure 1 – trees fall, water floods over, etc. The actual impact is identified when phenomena and their impacts are taking their toll on the transport system – power lines are cut, structures are washed away, infrastructure systems and the transport fleet are malfunctioning. A consequence is the result at the end of the causal chain where transport system performance indicators, such as safety, timeliness, and accessibility are affected. The line between these three essential concepts – phenomenon, impact and consequence – is indistinct and depends on the level of detail on which the causal mechanisms are modelled. But then again, the question is somewhat semantic and does not have added normative value.

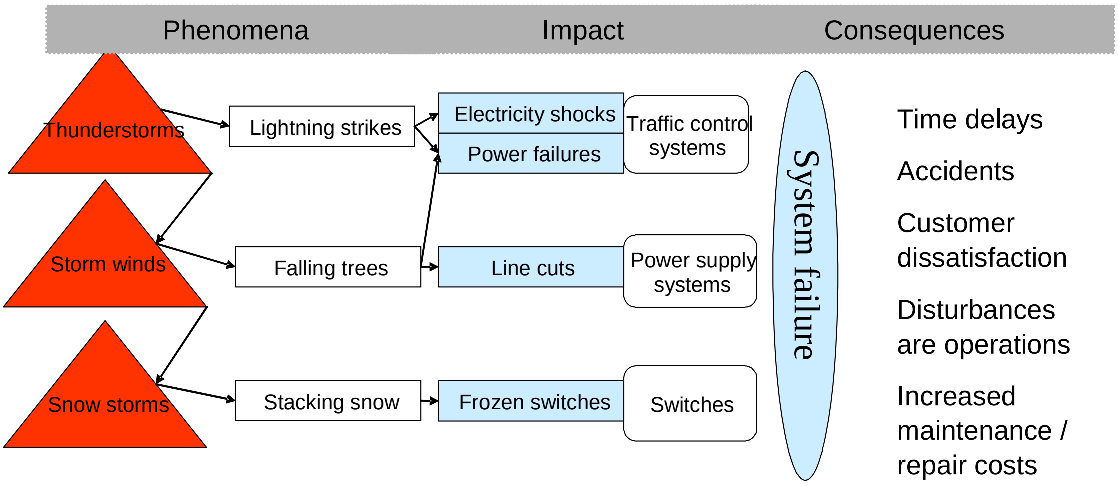
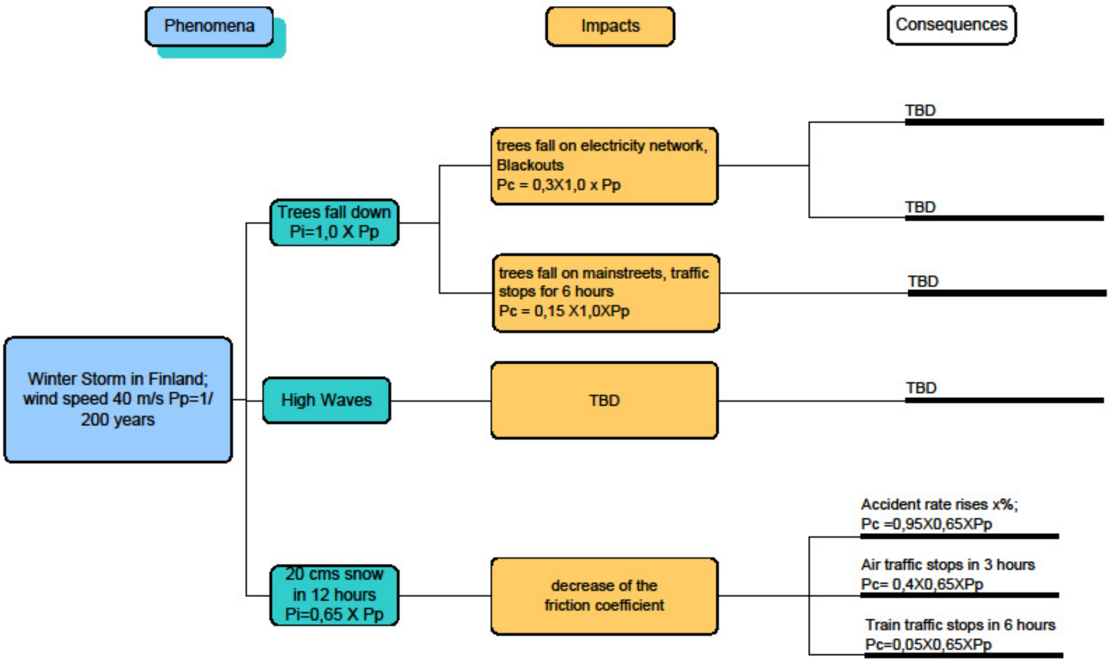


Figure 1. Simplified example of harmful weather impacts and consequences to rail transport.

Figure 2 shows how the causal map can be used to assess risk of consequences of different weather phenomena and impacts. The causal relationships contain many uncertainties along the chain, and to credibly assess true risk and vulnerability levels such uncertainties must be taken into account.



*TBD = to be determined

Figure 2. Linking phenomena, impacts and consequences in the EWENT context.

1.3 Method of research

The research methodology in EWENT's WP1 follows the traditional line:

1. Review of the literature and body of knowledge. Three sources are used: professional and scientific literature, media-reported cases, and detailed descriptions of extreme weather cases.
2. Synthesis on extreme weather phenomena and critical parameters. The critical parameter values form the decision-making criteria for EWENT's analysis on *ex ante* meteorological conditions. In simple words, threshold values for extreme weather phenomena are fixed in order to see how much the probability of occurrence of these phenomena will change in the future. Scenarios for future weather will be derived in WP2.

Preliminary hypotheses on causality between extreme weather parameters and impacts and consequences. The causal linkages are done on an a) empirical, b) logical and c) heuristic basis (Table 1). In some cases, past experiences provide a reliable starting point for assessing impacts and consequences. In others, we have to rely more on researchers' skills and knowledge. Whatever causal models are used, they are always logical, but the amount of empiricism and heuristics vary. Strictly analytical models are in practice not available.

The causal links are quantified to the extent enabled by EWENT project resources in WP3. The research process is depicted in Figure 3.

Table 1. Impact assessment model types (Leviäkangas & Hautala, 2009).

Model type	**Characteristics**	**Data need examples**
Analytical	Empirically validated, widely accepted model; produces results in "what-if" scenarios	Known input variables
Empirical, validated	Empirically validated, but the model validity is discussed or criticised; not widely accepted; can be used for *ex ante* scenario work	Suggested input variables
Empirical, unvalidated	Continuation of empirical experience, e.g. trend models; not valid if the underlying dependencies or mechanisms change	Historical data, time series
Logical-descriptive	The dependencies can be illustrated or described but not analytically quantified	No explicit or immediate data needs, some historical data or prior studies may back the argumentation; data serving deduction and induction; interviews and gathering of insights and experiences and other qualitative data usually utilised extensively
Heuristic	The model appeals to perception of the reality and included associations between associated phenomena	

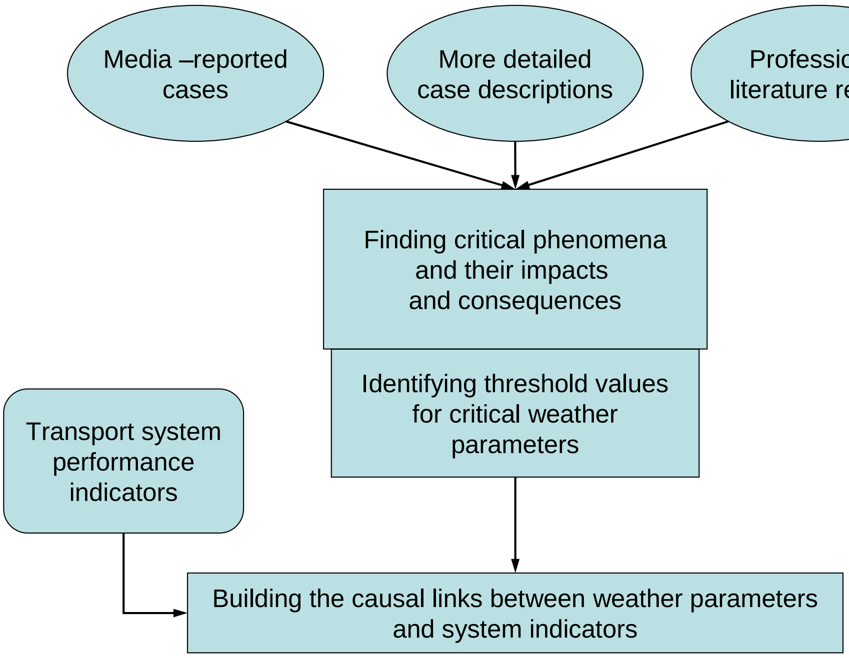


Figure 3. WP1 method of research. The last step interfaces with WP3.

2. What is extreme, where and to whom?

“Extreme” is not an exact concept. EWENT consortium researchers identified at least the following dimensions that are related to extreme weather phenomena with measurable and identifiable impacts and consequences:

Climatologic zone

Within EU-27, the same amount of snow during a day can be either extremely exceptional or common news. Hence the area of analysis needs to be zoned in order to take climatologic differences into account. The European Severe Storms Laboratory has created climatic zones for the EWENT project (see Figure 4.). This zoning is used as a starting point and can be further modified for alternative purposes.

Technological and institutional preparedness of Member States

Different parts of Europe have different resilience to extreme weather. In the Scandinavian countries, tackling of extreme colds and heavy snow precipitation is better because of a long history of learning and society’s investments in preparedness such as winter maintenance fleets. Some societies like the new Member States have been suffering from a lack of necessary resources to develop their resilience with regard to all aspects of the transport system: infrastructure in general is still of poorer quality in many places and institutional learning curves are at an early stage. Hence a heavy rainfall can probably be handled with less damage and fewer disruptions in Germany than in Lithuania.

There might also be clear political preferences on how many public resources are put to serving the transport system’s weather resilience in relation to other public investments and expenditures.

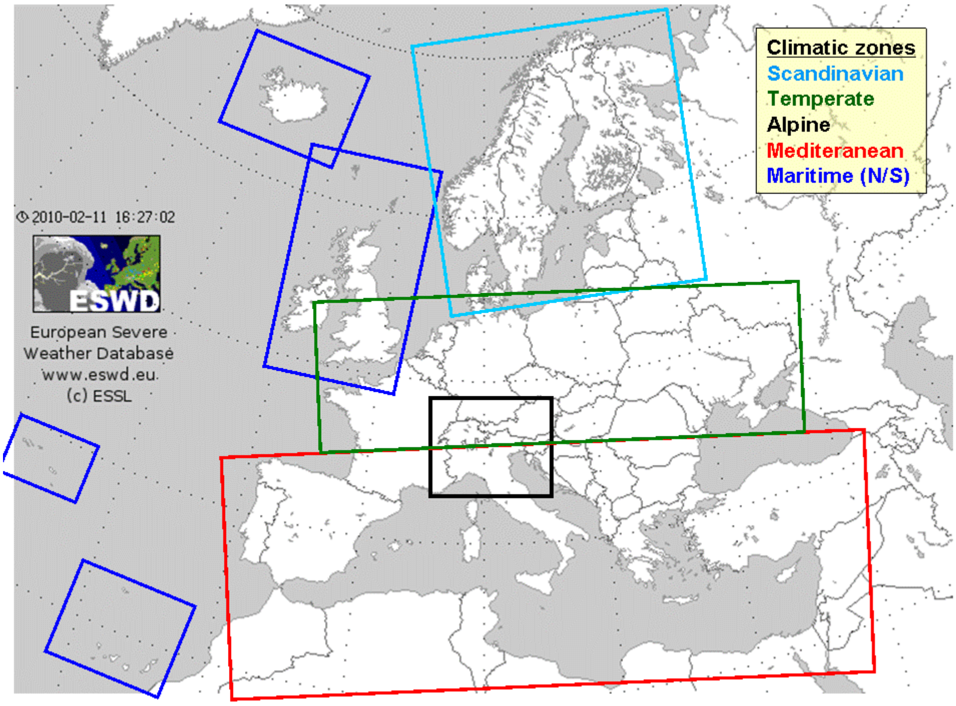


Figure 4. Proposed classification of climatologically similar European regions for EWENT.

Frequency on chronological or probability scale

Extremes may occur once a year, decade or century. The frequency of a phenomenon is one way of categorising chronologically the probability of an event. The probability can also be fixed, e.g. 1% probability, meaning in simple terms that as probability of an event is fixed and the time horizon is let to float. When speaking of flood the frequency is expressed as a return time, R; for example, R250 means a flood that occurs once in 250 years.

Intensity and severity of impacts and consequences

This is the most straightforward dimension in the classification of phenomena, since it explicitly reflects the research problem of EWENT. Extreme weather is something that has a consequence on the transport system. The more explicit and measurable the impacts and consequences are, the easier it is to identify critical weather phenomena.

Chronology of impacts and consequences

Extreme weather can be short-period, high intensity and immediate impact causing. Typically in these cases one witnesses almost immediate consequences, e.g. in the form of damaged infrastructures and disruptions in traffic flows. But there is also a more difficult dimension from a research point of view: Some weather phenomena could be slow evolving and have a huge aggregate impact in the course of time. For example, periods of close-to-zero temperatures deteriorate steel-concrete structures much faster than moderate colds and heats. According to some climate change scenarios, these types of weather could become more frequent in Scandinavia. This would also worsen road traffic safety (see Andersson, 2010).

Geographical dimension

Geographical location can enhance or diminish the harmful impacts of forceful weather phenomena. For example, dense forests and vegetated areas bind rainwater effectively and even out floods. On the other hand, forest areas can enhance the impacts of windstorms with trees falling all over the main roads and railways. Uncovered land is prone to erosion and increases flood impacts. Also steep topography fortifies flooding rivers and is one reason for avalanches.

Economic distribution effects

As always in the market economy, one man's loss is another man's gain. The cost impacts of deteriorating infrastructure will, for instance, benefit construction maintenance contractors. The need for better maintenance and various other services will increase the turnovers and profits for providers of services. In short, climate change and extreme weather phenomena will not make everybody worse off. The EWENT project does not consider the above distribution effects. They should, however, always be kept in mind.

In the context of the EWENT project the following definition for extreme weather events related to transport systems was developed:

Extreme events are generally rare events. The events cause the exceeding of maximum values and/or pre-existing (measured) high (low) thresholds of certain weather parameters and generate impacts that are harmful to any part of the transport system (infrastructures, operations, vehicles, passengers or cargo).

3. Literature and knowledge base for weather impacts on the transport system

3.1 Literature review per phenomena – some tentative critical weather parameter values

A review of the literature and existing body of knowledge on the impacts of extreme weather phenomena on transport systems was performed as part of EWENT. The survey was based on research papers published in national and international journals and books, reports of research projects and research councils.

Although focused mainly on European cases, most of the publications are concerned with extreme weather impacts from Canada, the USA and Australia. Each weather phenomenon was considered separately, including the delineated disruptive level and thresholds for it, the reported impacts and/or consequences on different transportation modes (road, rail transportation, aviation, navigation), and the country/city where the weather parameter has occurred. The phenomena included are: windstorm, snowfall/blizzard, hail, thunderstorm, tornadoes, flash floods/rainfall, volcanoes, extreme temperature (cold, hot), lightning, fog, freezing rain, frost and drought.

Table 2 summarizes the findings of the literature survey. The summary table contains weather phenomena, their critical parameter values and reported impacts and/or consequences on the transportation system published in professional literature. It also indicates the validity area of the findings and respective literature source. However, caution should be exercised when generalising the impacts, because specific features of single case studies might not always be applicable on a wider scale. Nonetheless, if there are no significant reasons why generalisation could not be done – meaning that the same type of phenomena on that region in similar circumstances could well lead to the same type of consequences – the validity is assumed to be fairly wide-ranging. Hence, for example studies carried out in the USA or Canada have almost without exception been assumed to be applicable throughout North America, but taking into account that the surrounding factors (land formation, landscape, vegetation, etc.) should be similar too.

The smaller grey font refers to climate change indices, which are referred to also in Table 2. These indices were gathered by the IPCC working group 40.

Table 2. Weather phenomena, critical parameter values, reported impacts and geographical validity.

	Windstorms			
Gust speed (m/s)	*Impacts on the transport system*	*Reference*	*Country of study*	*Validity area / region*
15	• Some fallen trees	Rauhala and Juga 2010	Finland	Northern Europe
17	• Trees fall over roads. Also electric power lines, telephone lines and street lighting poles may fall and cause danger, especially for road traffic. Trees can fall over cars. Cars and humans possibly stranded between fallen trees • Damage to mobile phone base stations may hamper the network • Boats may come loose from their moorings.	Rauhala and Juga 2010	Finland	Northern Europe
20	• A lot of fallen trees • Long lasting power failures cause problems such as people trapped in elevators, public facilities losing light, mobile phone network outages • Piled shipping containers may tip over • Road signboards may break off.	Rauhala and Juga 2010	Finland	Northern Europe
28	• Wide and long-lasting power failures possible	Rauhala and Juga 2010	Finland	Northern Europe
20 mph (32 kph)	• For road traffic a warning message – “CAUTION: WATCH FOR SEVERE CROSSWINDS” – • High-profile vehicles “NOT ADVISED” (Nevada).	Goodwin 2003	USA	North America
39 mph (63 kph)	• Advised to exit freeway • High-profile vehicles “PROHIBITED” (Nevada).	Goodwin 2003	USA	North America
	• Wind speed impacts • Visibility distance (due to blowing snow, dust) • Lane obstruction (due to wind-blown snow, debris) • Traffic speed • Travel time delay • Accident risk • Vehicle performance (e.g. stability) • Access control (e.g. restrict vehicle type, close road) • Evacuation decision support.	Goodwin 2003	USA	North America
	• Vehicle-related deaths account for 43% of non-convective wind fatalities: • Over 82% of all non-convective wind vehicle fatalities were in passenger cars or pickup trucks • Only 6% occurred in tractor trailers • 12% took place in other vehicle types (e.g. recreation vehicles, buses, motorcycles). Felled trees onto vehicles and vehicles striking felled trees represent 44% of fatalities associated with vehicular-related fatalities	Ashley and Black 2008	USA	North America

	• Blowing dust and snow compose 28% of vehicle fatalities • Boating fatalities represent 25% of all non-convective fatalities.			
80 kph 38 kph 97 kph	• Risk for the roadway sector of surface transportation • Moderate risk for transit vehicles • Restrict barge and tanker operations, disrupting fuel deliveries can cause physical damage to the pipeline system.	Peterson et al. 2006	USA	North America
37 kph 56 kph 46 kph	• Difficulties in small boat handling • Suspension of small boat operation • Damage at port facilities.	Peterson et al. 2006	USA	North America
39 knots	• Ferry service is stopped.	Andrey and Mills 2003b	Canada	North America
	• High winds blowing across roadways, bridges may prevent vehicles from crossing • Strong winds may blow snow or dust reducing visibility.	Pisano et al. 2002	USA	North America
	• Aviation accident due to very strong, gusty cross-winds: landing of a Transavia plane at Amsterdam Airport Schiphol in 1997.	Koetse and Rietveld 2007	Netherlands	Everywhere
29 m/s (58 knots)	• Accident of m/s Estonia on northern Baltic on 28 September 1994. More than 850 persons died and almost 140 persons were rescued. Strong winds prevailed during the night when the accident occurred and rescue operations were carried out (10 minute mean wind up to 23, gusts up to 29 m/s).	Komulainen 1994	Finnish coastal waters	Northern Europe
	Snowfall or blizzard *(heavy snowfall and strong wind)*			
Gust speed (m/s) with heavy snow fall	*Impacts on the transport system*	*Reference*	*Country of study*	*Validity area / region*
15	• Treetops or trees may bend under snow load • Cars stuck in snow banks, accidents on slippery roads • Trains and trams delayed.	Rauhala and Juga 2010	Finland	Northern Europe
17	• In road traffic a large risk for collisions with objects on roads because of poor visibility and slippery roads.	Rauhala and Juga 2010	Finland	Northern Europe
20	• Delays in air traffic, some flights transferred to other airports • Wind gusts may push cars off slippery roads.	Rauhala and Juga 2010	Finland	Northern Europe
	• Railway traffic disruptions with heavy snowfall, strong wind and low temperatures when railway points are filled with snow and warming is not sufficient • Disruptions when: Low temperature, wind and snow (Precipitation amount, 1 mm = ca. 1 cm of snow): • -7…-10 C, 4–7 m/s, 3 mm (ca. 3 cm snow) • -8…-12 C, 5–8 m/s, 10 mm • -10…-17 C, 6–10 m/s, 13 mm	Juga et al. 1983	Finland	Northern Europe

	• Mainly below zero, 7–10 m/s, up to 11.6 mm • -2…-7 C, 7–8 m/s, up to 16.2 mm • Clearly below zero, 8 m/s, up to 8.3 mm • Clearly below zero, strong wind, up to 21 mm Wind and snow: • 10–13 m/s wind and heavy snowfall • Gusty wind, up to 14 mm • Strong wind, 6.5 mm • 7–10 m/s wind, heavy snowfall Low temperature and snow • -20…-30 C, snowfall • -10 C, 5–15 mm • Below zero, precipitation up to 15 mm (15 cm snow) • Clearly below zero, 12.3 mm Snowfall • 7–10 cm snow • Precipitation amount 11.5 mm Wind • - 7 m/s wind with drift of earlier fallen snow.			
	• Dense snowfall, temperature -5…-8°C, supercooled water; - 300 cars crashed.	Juga and Hippi 2009	Finland	Northern Europe
	• Snow, rain or sleet on frozen surface -> highest road traffic accident risk.	Norrman et al. 2000	Sweden	Northern Europe
	Winter storm (snowfall of ≥:0.5 cm/h for more than 4 hours) • Road traffic volume reduction on average ca. 29% • Crash rates increase significantly • Snowfall intensity and duration increases crash frequency.	Knapp et al. 2000	USA	North America
	• Snow days less fatal crashes than dry days, but more non-fatal injury crashes (incidence rate ratio 1.23) and property damage crashes (1.45) • The first snow day of the year substantially more dangerous than other snow days (for fatalities IRR 1.14).	Eisenberg and Warner 2004	USA	North America
	• Snow-covered and frozen switches in rail infrastructure (ex. problems in rail transportation in Toronto after a heavy snowfall in January 1999).	Andrey and Mills 2003b	Canada (Toronto)	North America
Heavy snowfall, ≥ 3 cm in 6 hours	• Increases the collision risk in road transportation, risk ratio 2.42.	Andrey et al. 2003	Canada	North America
Snowfall in a wide area or some snowfall occurring at low temp. (< -10^{o}C)	• Typically high amount of traffic accidents occurred when a low pressure with snowfall came into Finland from west or southwest, causing snowfall over a wide area. Many peak days of traffic accidents were also related to very low temperatures with some (local/occasional) snowfall, which was packed on the road surface by traffic (at very low temperatures salting is typically not carried out).	Sihvola et al. 2008	Finland	Northern Europe

Frequent snowfalls during winter 2005/06	• During most of the winter 2005/06 in Central Europe (especially in southern Germany and Austria), there were a large number of weather-related hazards due to snowfall events. The road traffic was disrupted by snow and ice covered roads, resulting in a high amount of car accidents. Many roads were also blocked by fallen trees. The winter was not extreme in terms of low temperatures. However, temperatures somewhat below freezing caused the average precipitation to fall mostly in the form of snow.	Pinto et al. 2007	Central Europe	Central Europe
	Hail			
Size (cm)	*Impacts on transport system*	*Reference*	*Country of study*	*Validity area / region*
≥ 1.5/ long duration	• Slippery roads and poor visibility.	Rauhala et al. 2009	Finland	Everywhere
2–3	• Occasional damage to car sheet metal.	Rauhala et al. 2009	Finland	Everywhere
3–5	• Damage to car sheet metal and windshields cracked.	Rauhala et al. 2009	Finland	Everywhere
≥ 7	• Car windshields completely broken, large dents in sheet metal.	Rauhala et al. 2009	Finland	Everywhere
≥ 7	• Damage to 70 000 vehicles and 23 aircraft.	Schuster and Blong 2004	Sydney, Australia	Australia
	Thunderstorm wind gusts			
Gust speed (m/s)	*Impacts on transport system*	*Reference*	*Country of study*	*Validity area / region*
F1 (33 m/s)	• A lot of trees fall on roads, electric power lines, telephone lines and on street lighting lines • A risk for collisions with trees on roads or wind may push cars off road. Trees can fall on cars • Small boaters possibly in distress. Boats may come loose from their moorings • Trees may fall onto railways • Power failures.	Rauhala and Mäntyniemi 2010	Finland	Northern Europe
F2 (50 m/s)	• A lot of fallen trees • Trees may block even wide sections of roads • A lot of people possibly stranded between fallen trees over roads and in buildings.	Rauhala and Mäntyniemi 2010	Finland	Northern Europe
26 m/s	• "When examining derecho fatalities by type, boating and vehicular deaths accounted for nearly 50% of all fatalities. In the majority of cases, vehicular fatalities occurred in one of three ways: • 1) overturned tractor semi-trailer, 2) felled tree landing on automobile, or 3) an automobile driven into a felled tree. Marine fatalities principally occurred as drownings when either sailing vessels or motorized boats were overturned due to high derecho winds.	Walker and Mote 2005	USA	North America

	• Major cause of Chicago area power interruption.	Bertness 1980	USA (Chicago)	North America
	• 27 commercial aviation accidents linked with thunderstorm wind shears between 1964 and 1982.	Riebsame et al. 1986	USA	North America
	Flash floods/rainfall			
Rainfall (mm)	*Impacts on transport system*	*Reference*	*Country of study*	*Validity area / region*
100	• The sewer system fills up; water rises to street level from drains • Rainwater fills underpasses and lower lying streets. Drain well covers may become detached and cause danger to street traffic.	Rauhala and Mäntyniemi 2010	Finland/ in towns	Nordic countries
140	• Road structures may collapse and gravel roads are badly damaged. Bridges may be flooded. Several streets needed to be closed leading to stranded buildings • If a car is driven into deep enough water, the motor stops and may be flooded.	Rauhala and Mäntyniemi 2010	Finland/ in towns	Nordic countries
	• In May 1995 a rain event caused widespread flooding in Dallas, resulting in seven roadway fatalities at stream locations near roads.	Goodwin 2003	USA	USA
	• Precipitation impacts (type, rate, start/end times) • Visibility distance • Pavement friction • Lane obstruction • Roadway capacity • Traffic speed. • Travel time delay • Accident risk • Vehicle performance (e.g. traction) • Driver capabilities/behaviour • Road treatment strategy • Traffic signal timing • Speed limit control • Evacuation decision support • Institutional coordination.	Goodwin 2003	USA	North America
	• 63% of flood fatalities with known activities or locations occurred in vehicles.	Ashley and Ashley 2008	USA	North America
> 10 mm after a dry spell of > 5 days	• 30% increase in crash risk on roads compared with wet days not in spells.	Keay and Simmonds 2006, 2005	Australia (Melbourne)	Australia
> 1 mm after dry spells of 1–5 days	• 5% increase in crash risk on roads compared with wet days not in spells.	Keay and Simmonds 2006, 2005	Australia (Melbourne)	Australia
> 25 mm	• Probability of car accident occurrence is greater than during any other rain conditions.	Sherretz and Farhar 1978	USA (St. Louis)	Australia
	• Flood affects road and rail infrastructure, bridges, bridge foundation, ex. floods along Mississippi River, summer 1993.	Mills and Andrey 2002	USA	North America
	• Heavy rain: very low visibility, lane submersion, flooded underpasses, damage to roadbeds.	Pisano et al. 2002	USA	North America

	• Floods and sea level rise cause problems in coastal road transportation, airports, coastal navigation.	Andrey and Mills 2003	Canada	North America
	• Rainfall-induced landslides, e.g. the 1997 mudslide in the Fraser Canyon that washed out a section of CN track near Lytton, derailing a freight train.	Andrey and Mills 2003b	Canada	North America
Heavy rain, ≥ 10 mm over 6 hours	• Increased collision risk on roads, risk ratio 1.86.	Andrey et al. 2003	Canada	North America
> 25.5 mm	• Increase in number of road accidents on rainy days, especially when heavy rain occurred • 90% of heavy rain days had delays in flight departures.	Bertness 1980	USA (Chicago)	North America
	• Floods afterwards caused severe damage to the metro system: track switch motors, signalling system, power distribution systems, tracks, escalators, total damage $10 million (Boston), $35 million (Seoul), $60-140 million (Taipei).	Compton et al. 2002	USA (Boston), South Korea (Seoul), Taiwan (Taipei)	North American metropolitan areas
	• Flash flooding in Chicago in 1996: damaged bridges and streets, delayed trains.	Peterson et al. 2006	USA (Chicago)	North American metropolitan areas
	• Erosion of road base and bridge support, reduced clearance under bridges • Overloading of drainage systems causing backups and street flooding, road wash-out, damage to rail bed support structures, landslides, mudslides, impacts on soil-moisture levels, affecting structural integrity of roads, bridges and tunnels • Impacts on harbour infrastructure from wave damage and storm surges • Delays, flooding, at airports, runway and other infrastructure damage.	National Research Council 2008	USA	North America
RR ≥ 10 mm	• Number of heavy precipitation days, recommended by ETCCDMI.	ETCCDMI web-page, Alexander et al. 2006; Klein Tank and Können 2003; Kiktev 2009, Klein Tank et al. 2009	Worldwide	
RR ≥ 20 mm	• Number of very heavy precipitation days, recommended by ETCCDMI.	ETCCDMI web-page, Alexander et al. 2006; Klein Tank and Können 2003; Kiktev 2009, Klein Tank et al. 2009	Worldwide	

RR 95%	• Very wet days: Annual percentage of heavy precipitation (above a 95 quantile of the 1961–1990 daily precipitation distribution) in the total annual precipitation; recommended by ETCCDMI.	ETCCDMI web-page, Alexander et al. 2006; Klein Tank and Können 2003; Kiktev 2009, Klein Tank et al. 2009, Moberg et al. 2006	Worldwide	
RR 99%	• Extremely wet days: Annual percentage of heavy precipitation (above a 99 quantile of the 1961–1990 daily precipitation distribution) in the total annual precipitation; recommended by ETCCDMI.	ETCCDMI web-page, Alexander et al. 2006; Klein Tank and Können 2003; Kiktev 2009	Worldwide	
RR 5day	• Highest five-day precipitation in a year; recommended by ETCCDMI.	ETCCDMI web-page, Klein Tank et al. 2009	Worldwide	
	Tornadoes			
Gust speed (m/s)	*Impacts on transport system*	*Reference*	*Country of study*	*Validity area / region*
F1 (33)	• A lot of trees fall or snap • High risk of road traffic colliding with falling trees.	Rauhala and Mäntyniemi 2010	Finland	Nordic countries
F2 (50)	• In large areas roads and telephone lines out of order, power failures • Wind may throw debris onto runways, leading to airport closures • Small boats may become airborne due to wind.	Rauhala and Mäntyniemi 2010	Finland	Nordic countries
F3 (70)	• Railway carriages tip over.	Rauhala and Mäntyniemi 2010	Finland	Nordic countries
	• 9.9% of all tornado fatalities vehicular-related.	Ashley 2007	USA	North America
	Volcanoes			
Ash downfall, in airspace or lava flows	*Impacts on transport system*	*Reference*	*Country of study*	*Validity area / region*
Few mm-several cm (max. registered 50 cm)	• Ash fall causes reduced visibility, creates slippery runways, infiltrates communication and electrical systems, interrupts ground services and damages buildings and parked airplanes.	Guffanti et al. 2009	Ecuador (Quito)	South America

Ash in airspace	• Reduced visibility, damaged aircraft, disrupted operations or closed airports.	Guffanti et al. 2009; Albersheim and Guffanti 2009	Japan, Italy, Guatemala, Chile, USA (Washington), Alaska	Everywhere
Pyroclastic flows		Guffanti et al. 2009	British West Indies (Montserrat)	
Lava flows	• Lava flows onto runway.	Guffanti et al. 2009	Congo	Africa
Lava flows	• Buildings, runways and other infrastructure are destroyed.	Guffanti et al. 2009	Japan	Everywhere
No min. ash fall down accumulation threshold		Peterson et al. 2006	USA	
	Extreme temperature: cold			
Temperature (°C)	*Impacts on transport system*	*Reference*	*Country of study*	*Validity area / region*
T < -29°C	• Limitation to ground crew work at airports and along roadways • First occurrence of low T at 0°C can produce rail contraction that can cause gaps and misalignment of the track.	National Research Council 2008; Peterson et al. 2006	USA	North America
T < -	• So-called “temporary slow orders” for trains due to cold • Winter train length policy.	Andrey and Mills 2003	Canada	North America
T = 0°C daily air temp.	• Freeze-thaw cycle: increased frequencies of freeze-thaw cycles result in premature deterioration of road and runway pavements.	Mills and Andrey 2002	Canada	North America
Permafrost T > -2°C	• Permafrost degradation may compromise the stability of paved airport runways and all-season road and rail bases.	Mills and Andrey 2002	Canada, Alaska	Northernmost America
	• Broken railway lines and wheel wear • Snow-covered and frozen switches (ex. problems in rail transportation in Toronto after a heavy snowfall in January 1999).	Andrey and Mills 2003	Canada (Toronto)	North America
T<-28.9°C (-20°F) for more than 1 h + wind speed > 10 mph	• Threshold for dangerous wind chill (from “Weather threshold with implications to US transportation primarily derived from NWS forecasting directives).	Peterson et al. 2006	USA (Western region)	

Tdmin <10%	• Cold spell duration index (CSDI): annual count of days with at least 6 consecutive days when T daily minimum < 10th percentile, recommended by ETCCDMI.	ETCCDMI web-page, Alexander et al. 2006; Klein Tank and Können 2003; Kiktev 2009, Klein Tank et al. 2009, Moberg et al. 2006	Worldwide	
	Extreme temperature: heat			
Temperature (°C)	*Impacts on transport system*	*Source*	*Validity area*	
Heat index ≥ 38°C for several hours	• Buckling of road surface that may lead to their closure • Public transportation (electric commuter trains) stopped because of power outages and heat.	Palecki et al. 2001	USA (Chicago, St. Louis	North America
T ≥ 26°C T ≥ 25°C	• Increased crash rate in road transportation • Fatigue among bus-drivers and truck-drivers.	Rowland et al. 2007	Australia	Australia
T = 29.5°C T ≥ 32°C T ≥ 43°C	• Restrictions in road maintenance and construction • Roadway buckling • Rail equipment failure, rail track buckling.	Peterson et al. 2006	USA	North America
	• Pavement softening and traffic-related rutting • Buckling of pavement, flushing or bleeding of asphalt from older or poorly constructed pavements • Buckling of railway track (rail incident in Maryland, July 29, 2002.	Mills and Andrey 2002 Andrey and Mills 2003	North America (Canada, USA)	North America
T = 29.5°C T = 40.5°C T = 32°C T = 43°C	• Thermal expansion on bridge expansion joints and paved surfaces • Restrictions in road maintenance and construction • Heat exhaustion • Concerns regarding pavement integrity, e.g. softening, traffic-related rutting, migration of liquid asphalt • Rail-track deformation.	National Research Council 2008	USA	North America
Tdmax > 25°C	• Number of summer days (annual count), recommended by ETCCDMI.	ETCCDMI web-page, Alexander et al. 2006; Klein Tank and Können 2003; Kiktev 2009	Worldwide	
Tdmin > 20°C	• Number of tropical nights (annual count), recommended by ETCCDMI.	ETCCDMI web-page, Alexander et al. 2006; Klein Tank and Können 2003; Kiktev 2009	Worldwide	

Tdmax > 90%	• Warm spell duration index (WSDI): annual count of days with at least 6 consecutive days when T daily maximum > 90th percentile, recommended by ETCCDMI.	ETCCDMI web-page, Alexander et al. 2006; Klein Tank and Können 2003; Kiktev 2009; Klein Tank et al. 2009 ; Moberg et al. 2006	Worldwide	
	Lightning			
	Impacts on transport system	*Reference*	*Country or origin of the study*	*Validity area or region*
	• Airplane crash because of lightning strike while holding pattern.	Curran et al. 2000	USA (Maryland)	
	• The frequency of fatalities in transportation is 10%.	López et al. 1995	USA (Florida)	
	• Disruption to power, communication and control systems, e.g. traffic signal system, ramp gates.	Pisano et al. 2002	USA	
	Fog			
Visibility (m)	*Impacts on transport system*	*Reference*	*Country or origin of the study*	*Validity area or region*
	• Fog-related crash involving 193 vehicles on a 11.3 km bridge, resulting in the following warning system: When visibility • less than 274.3 m: reduced speed limits, fog warning • less than 53.3 m, road closure. • Nineteen fog-related crashes occurred in the 4-year period before the motorist warning system was deployed; after, none. Criteria: • Visibility distance between 61–152.4 m “FOGGY CONDITIONS AHEAD” • Visibility less than 61.0 m “DENSE FOG AHEAD”. • On December 11, 1990 in Tennessee the visibility distance was less than 3.1 m and the extremely low visibility contributed to chain-reaction collisions involving 99 vehicles, 42 injuries, and 12 fatalities.	Goodwin 2003	USA	North America
	• Fog impacts • Visibility distance • Traffic speed • Speed variance • Travel time delay • Accident risk • Driver capabilities/behaviour • Road treatment strategy • Access control • Speed limit control.	Goodwin 2003	USA	North America
< 53.3 m (175 feet)	• Road closure on highways.	Goodwin 2003	USA (Alabama)	

< 73.2 m (240 feet)	• Road closure on highways.	Goodwin 2003	USA (Tennessee)	
3.8 km	• Transit trains suspended.	Peterson et al. 2006	USA	
< 800 m < 400 m	• Two-way navigation suspended • All vessel movements stopped.	Peterson et al. 2006	USA	
	• Low visibility: increased risk of chain-reaction crashes.	Pisano et al. 2002	USA	North America
	Freezing rain			
Rainfall (mm)	*Impacts on transport system*	*Reference*	*Country or origin of the study*	*Validity area or region*
10 cm ice accumulation, also 22 m/s wind gusts	• At least 500 000 people experienced power failure • Falling of ice laden tree limbs • Traffic accidents.	Bendel and Paton 1981	Wisconsin, USA	
RR = ?, Tmin = -1.7°C	• Black ice on road, as rain and drizzle froze on impact: closed roads, series accidents.	Symons and Perry 1997	Southern England	British Isles
Cloud top: 0 and -10°C, and surface T > 0°C	• Hazardous in-flight icing situation in aviation.	Carriere et al. 2000	Western, Central Europe, Scandinavia	Europe
	Frost			
	Impacts on transport system	*Reference*	*Country or origin of the study*	*Validity area or region*
Ts < 0 Ts < Td Td~0 or >> Ts	• "Frost on bridges and roadways leads to considerable damage to vehicles, structures, and trees as well as occasional injury and loss of life due to motor vehicles going out of control on slippery surfaces" • "Bridges develop more often widespread frost because of radiational cooling".	Takle 1990	USA	North America
T = 0°C daily air temp.	• Freeze-thaw cycle: increased frequencies of freeze-thaw cycles result in premature deterioration of road and runway pavements.	Mills and Andrey 2002	Canada	North America
Permafrost T > -2°C	• Permafrost degradation may compromise the stability of paved airport runways, all-season road and rail bases.	Mills and Andrey 2002 National Research Council 2008	Canada, Alaska, USA	North America
Tmin ≤ 0°C (32°F) in the next 12–36 h	• Freeze warning issued (from "Weather threshold with implications to US transportation" primarily derived from NWS forecasting directives).	Peterson et al. 2006	USA	USA

Tdmin < 0°C	• Number of frost days (annual count of days), recommended by ETCCDMI.	ETCCDMI web-page, Alexander et al. 2006; Klein Tank and Können 2003; Kiktev 2009	Worldwide	
Tdmax < 0°C	• Number of icing days (annual cont), recommended by ETCCDMI.	ETCCDMI web-page, Alexander et al. 2006; Klein Tank and Können 2003; Kiktev 2009	Worldwide	
Long winter, temp. somewhat below 0^{o}C, lack of thawing	• Boat traffic on the river Danube was disrupted between January and March due to thick river ice cover. This was caused by a long winter with temperatures somewhat below freezing and lack of significant thawing periods. The following snowmelt in spring led to extensive floods in the Danube and Elbe rivers.	Pinto et al. 2007	Central Europe	
	Drought			
Precipitation	*Impacts on transport system*	*Reference*	*Country or origin of the study*	*Validity area or region*
	Inland waterway traffic: • Goods traffic: decrease of draught by 1 cm corresponds to a decrease of cargo by 10 000 kg • Floating: if draught is less than 1.8 (needed by a tugboat) the transport is interrupted • Passenger traffic: embarkation from pier is more difficult, grounding risk, ferryboats have difficulties operating.	Silander and Järvinen 2004	Finland	Finland
> 10 mm after a dry spell of > 5 days	• 30% increase in crash risk on roads compared with wet days not in spells.	Keay and Simmonds 2006	Australia (Melbourn)	Australia
> 1 mm after dry spells of 1–5 days	• 5% increase in crash risk on roads compared with wet days not in spells.	Keay and Simmonds 2006	Australia (Melbourn)	Australia
6 dry days > 21 dry days	• 17.9% increase in crash risk on roads compared with wet days not in spells • 23.1% increase in crash risk on roads compared with wet days not in spells.	Eisenberg and Warner 2004	USA	North America
	• Closed highways or airstrips because of forest fires during drought e.g. Ontario, spring 1999.	Andrey and Mills 2003	USA (Ontario)	
	• Welfare loss of 91 million euro in 2003 due to the very dry summer.	Koetse and Rietveld 2007	Europe river Rhine	

3.2 Literature review by transport mode

3.2.1 Road transport

Specifically relevant scientific articles were difficult to find on the Internet, and only a few articles were identified that focused on the geographical area and time period under review in regard to weather-related consequences to traffic or transportation.

Road accidents are typically a consequence of the combined effects of several different factors broadly grouped as behavioural, technological and environmental. The absence of any one of these contributing factors could prevent an accident from occurring. Road vehicles, unlike certain other forms of transport, are not designed for extremes of weather; they are intended for use within a limited range of weather conditions. (Edwards, 1996)

In addition, technical advances have further complicated the picture. Developments such as anti-lock brakes, four-wheel drive and traction control have all improved vehicle handling under poor conditions. As a result, drivers may be taking greater risks than they might otherwise have done in the past, as they feel more confident when driving vehicles equipped with these safety features. Alternatively, in certain circumstances, such as snow, people take more care by reducing their speed accordingly, and are thus able to negate the increased hazard. It may also then be the case that some journeys are cancelled, postponed or re-routed, which leads to a reduction in the number of vehicles at risk. (Edwards, 1996)

Therefore, it is interesting that according to the latest Road Traffic Accidents Statistics in Finland (Statistics Finland, 2009), both fatal accidents and those leading to injuries happen mostly during the time period from May to October. The accident reports also provide information about the weather conditions for which most of the accidents occurred – dry roads and daylight conditions, but involving higher speeds. Obviously it is important not to forget that a string of other factors is typically involved, such as traffic density and flow, the familiarity of the roads (e.g. holiday conditions) and even alcohol consumption. The second-most accident-related weather condition simply involved a wet road surface. However, even under snowy and slushy or icy conditions accident-related casualties and fatalities were unusual when the traffic route had been cleared.

According to statistical data and research findings, weather-related causes such as limited visibility conditions through fog, heavy rain or snow and slippery roads play only a minor role in the development of road accidents involving personal injury. In 1999, 10% of the injuries documented in Germany were attributable to adverse weather conditions. In addition to driving conditions, weather conditions usually have an influence also on rescue times, which may subsequently affect the severity of injuries. (Maaz, 2004)

A study showed that in the Nordic countries (Denmark, Finland, Norway and Sweden) the number of traffic accidents increased in the rain, but showed a lower incidence of accidents on snow, with the exception of the first snow of the year. According to the study, the increased number of accidents in the summer can be correlated to increased road traffic. The decreased injury severity in the winter months may be associated with lower driving speeds in adverse road conditions. (Maaz, 2004)

Snowfall typically has a negative impact on driving conditions, as it decreases the road surface friction and reduces visibility. Especially if the temperature is too low (<-5°C) for salting to be effective, or if the snowfall intensity is too high for effective snow removal, there will likely be disturbances in traffic with high accident rates (Rauhala & Juga, 2010). In Sweden, based on a three-year study, 50% of all road traffic accidents during winter occur in association with slippery road conditions. The highest accident risk in southern Sweden is when rain or sleet falls on a frozen road surface. The second most hazardous road condition is when snowfall and frost formation occur at the same time. Under these conditions, accidents seem to occur in spite of full maintenance activity. So, in order to reduce the amount of accidents, public awareness should be increased. (Norrman et al., 2000)

According to Bijleveld & Churchill (2009), it is somehow problematic to use results obtained from studies performed in other countries. Results should be adapted to conditions in other countries, since general climate may have an impact on how road users react to changes in weather conditions. In the study, the effects of weather conditions on road safety in the Netherlands were analysed, the focus being on precipitation. The results determined that the impact of precipitation appeared to be more severe during the winter months than at other time periods. Previous time-series studies also showed that the number of fatalities almost doubled under conditions involving precipitation, and that the number of fatalities and casualties more than doubled. The previous results also indicated that the effects in autumn and winter were larger than in spring and summer.

Edwards (1996), in her study of accidents in England and Wales, established that the reporting of accidents in hazardous weather broadly followed the regional weather patterns for those hazards. It was evident that the vast majority of accidents occurred during non-hazardous fine weather. Overall, rain was seen to be the most common hazard. High winds were also most prevalent in western and northern regions although less than 5% of all accidents occurred during these conditions. Accidents in fog and snow were highly seasonal and therefore relatively insignificant.

In a subsequent study, Edwards examined the actual accident severity during adverse weather, such as rain, fog and high wind, in England and Wales (Edwards, 1998). The findings established that accident severity actually decreased significantly under rainy conditions compared with fine weather, while the severity in foggy conditions showed geographical variation. Evidence for accident severity in association with high winds remained inconclusive.

According to the Lambe & Cummings (2000) study, the effects of weather and visibility do not have a significant influence on the number of road accidents. No impacts could be detected on accident rates in relation to either the change to/from “daylight saving” time, or changing twilight times.

Although weather conditions are often not the direct cause of an accident, they typically indirectly affect users; i.e. the frequency or type of participation in traffic and in particular on behaviour leading to an accident. Thus, bad weather and poor road weather conditions only contributed to 4.8% of all aspects that have been identified by the German police in accidents involving personal injury. The foremost cause of accidents was deemed to be the iciness/slipperiness of the road or rain. Overall, general causes, to which also the weather and road conditions and obstacles (e.g. wild animals) belong, contributed to 8.9% of accidents. A summary of the German road accident statistics for 2008 shows that in bad weather, and especially in wintery conditions, more accidents are registered, but they have less severe consequences. In contrast, most casualties are observed in the months with better weather conditions. In 2008, good weather during spring resulted in, according to the statistics, more severe accidents in Germany. During bad weather conditions there were less severe accidents; also the incidence of bicycle accidents declined. (Statistisches Bundesamt, 2009)

For example, in Germany during December 2009, as the winter weather descended upon Europe (with snow and frost) the amount of accidents (and the costs of accidents) rose in comparison to the previous December – although, as previously noted, the amount of fatalities and seriously injured declined. (Statistisches Bundesamt, 2010; see Table 3)

Table 3. Accident development on German roads. (Statistisches Bundesamt, 2009, Statistisches Bundesamt, 2010). *(Note: only main sub-causes displayed)*

Causes of accidents involving personal injury					
General causes	**2005**	**2006**	**2007**	**2008**	**2009***
Total	**40 136**	**35 675**	**39 345**	**40 068**	**41 866**
Including:					
– Slippery due to rain	8 598	7 837	10 032	8 672	8 498
– Slippery due to snow/ice	12 359	9 754	5 230	6 033	9 761
– Obstructions by fog	597	518	377	484	406
– “*Wild*” on the road	2 291	2 381	2 617	2 614	2 412
Technical defects in vehicles	**4 402**	**4 302**	**4 436**	**4 158**	**3 962**
– Tyres	1 233	1 214	1 213	1 145	1 184
– Brakes	784	727	774	757	669

** Preliminary results*

Increased occurrence of extreme events (e.g. heat waves) may lead to a loss of personal comfort and subsequent disruptions to public and private transport. The "century-floods" in Vienna in August 2002 revealed extreme weather impacts on car, rail and boat transport. The main underground lines (U1 & U4) were in partial use for several days due to safety concerns. Indications are that the protective measures prevented even greater loss (cf. the situation in Prague was much worse, with 17 of the 51 stations of the three routes completely flooded). Several rail and bus lines had to be either rerouted or cancelled, and restrictions applied also to motorists. (Kromp-Kolb et al., 2007)

In a study on the role of the environmental aspects in Belgian road accidents, a relationship was identified between the number of days with thunderstorm and most of the traffic safety variables (i.e. a thunderstorm generally decreases traffic safety). Furthermore, a higher monthly percentage of days with frost also led to a decrease in all the dependent variables. Recorded days of snow was not significant in the models, almost entirely because snow is not common in Belgium. A higher percentage of days with sunshine did not significantly alter the traffic safety outcomes. The results confirm that the effect of weather is related to the geographical characteristics of the area and the considered period. (van den Bossche et al., 2005)

3.2.2 Rail transport

Safety, reliability and accuracy are traditionally considered as the main quality dimensions for rail transport. Extreme weather may cause impacts and consequences affecting these dimensions, lowering the level of rail transport services. The following potentially harmful weather-related phenomena for rail transport were indentified from the literature: These include flooding, avalanches, landslides, melting permafrost, and hot and cold waves. As regards winter conditions, low temperatures (especially over long time periods), snowfall and strong wind gusts were identified as the most harmful combination of winter weather phenomena for rail transport.

Precipitation

Increasing intensity of rainfall increases runoff and flooding of low-lying highways and railways. Also, an increased storm surge is likely to affect highway access and use. Flooding (tidal, river and surge floods) affects the grounding of railways and their electricity, as well as telecommunication systems across the entire rail transportation network. Flood amplification is a real concern. Rain runoffs quickly undermine structures such as dams, railway beds, bridges, and buildings. In the future, tunnels may become more vulnerable, both because the risk of their entrances and vents flooding will be greater, and because the hydraulic pressure on tunnel walls increases as water tables rise (Titus, 2002).

Thunderstorms

Thunderstorm activity may harm rail operations through various means, including lightning strikes to switching equipment, flash floods of poor drainage areas, and high winds associated with microbursts and squall lines.

Winter storms/snow

Winter storms bring heavy snow to Northern and Central Europe, which causes delays because trains are not able to plough the tracks or melt the ice cover from them. Drifting snow causes freezing of the rail points. Severe winter storms disrupt the entire transportation system. Railway operations are degraded by lowered visibility, icing, snowdrifts, and cold temperatures. Railway segments dependent on overhead electrical catenaries may fare especially poorly since their exposure tends to allow ice build-up.

Freeze-thaw cycles

Global warming is assumed to increase the frequency of freeze-thaw cycles. As this occurs, the roads, railways, and airport runways in Middle Europe will suffer attendant problems and maintenance costs are likely to increase.

Cold waves

Cold waves in winter pose special challenges to hydraulic and electric train systems. When the temperature falls to around -30ºC, individual train elements become very fragile and break down easily. Extreme cold weather can also result in brittle tracks, increasing the risk of breakage (Rossetti, 2002).

Avalanches

Avalanches could pose a seasonal threat to railway operations in the Alpine area. However, Alpine railways appear to be well protected as no accidents of this nature have been reported over the last ten years.

Heat

Railway tracks are subject to buckling from extreme heat. When exposed to the hot summer sun, railway tracks occasionally develop heat kinks that may create hazardous conditions for traffic. Track misalignments caused by sun kinks have often been identified as a cause of train derailments with the potential for injuries, fatalities, property damage, and toxic release of hazardous materials (Rossetti, 2002). Railway tracks may also be exposed to uneven thermal expansion when shade covers nearby sections, thereby posing the risk of warp and misalignment to freight traffic.

Extreme high temperatures are associated with increased incidences of rail buckles. Climate change is predicted to increase the frequency of extreme high temperatures, raising the number of buckles and causing a lot of delays. For example in the United Kingdom it has been estimated that the costs incurred as a result of the hot summer of 2003 will become typical in the 2050s (high emissions scenario) and 2080s (low emissions scenario). It is estimated that the total costs of heat-related delays will eventually double to nearly £23 M during extreme summers if no changes are made to maintenance systems. (Dobney et al., 2010)

Melting permafrost in the northern part of Scandinavia could cause landslides, closing railways and roads and isolating rural areas.

Sea-level rise

Sea-level rise ranging from a global mean is one likely outcome of global climate change and will be fatal in areas where land is subsiding (Houghton et al., 2001). These kinds of areas in Europe are located in the Baltic Region and the Netherlands. Together with winter storms, changes in sea level may damage low-lying coastal infrastructure including road and railway beds, port and airport facilities, tunnels and underground rail/subway/transit corridors. (Mills and Andrey, 2002).

3.2.3 Land transport infrastructures

Weather impacts on road transport infrastructure

The most harmful weather phenomena for road transport infrastructure are heavy snowfall, heavy precipitation, low temperatures and wind gusts (see conceptual maps in Figures 5 and 6). Naturally a combination of these phenomena (e.g. a blizzard) makes conditions very difficult and may cause widespread damage.

Heavy rain may cause landslides and mud flows that rapidly destroy roads, or flooding that erodes road structures. Flooding can damage pavements and bridges as well as culvert and drainage pipes. Flooding water can also end up in underground transport systems. But other phenomena than rain can also cause flooding. Melting snow, ice dams and also heavy wind in areas near the sea may lift water levels to abnormal levels. Landslides, mudflows and flooding may all, in the worst case, cause destruction of roads.

Snow and freezing rain make road surfaces slippery and visibility poor, which slows traffic and causes accidents. Heavy snow can also block roads. Also wind gusts can block roads by felling trees and affecting vehicle behaviour, increasing the probability of accidents. Winds approaching tornado force may also directly damage vehicles, bridges and equipment, as does hail in extreme cases. Changes in temperature affect materials: frozen materials become brittle, and temperature-based expansion and shrinking can loosen stones in cuttings, causing them to fall across and block roads.

Weather phenomena and their impacts and consequences form a complex net where many different phenomena, alone or together, can have the same impact and result in a whole range of consequences. In Figure 6, for example, wind causes the sea level to rise. There are also many different phenomena that may lead to flooding also, all with different probabilities. The consequences of flooding are many – some more severe than others, some more likely to happen than others, and some rapid and some having effects over a longer period of time.

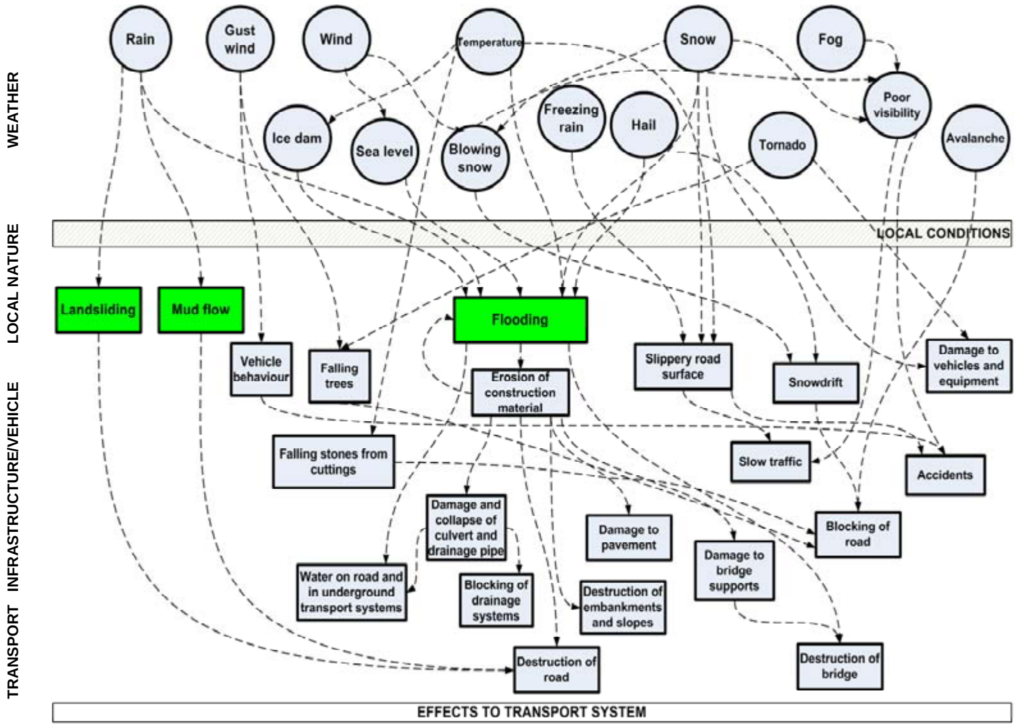


Figure 5. Conceptual map of weather phenomena impacts on road infrastructure and transport (source: Makkonen, Törnqvist and Kuusela-Lahtinen, VTT).

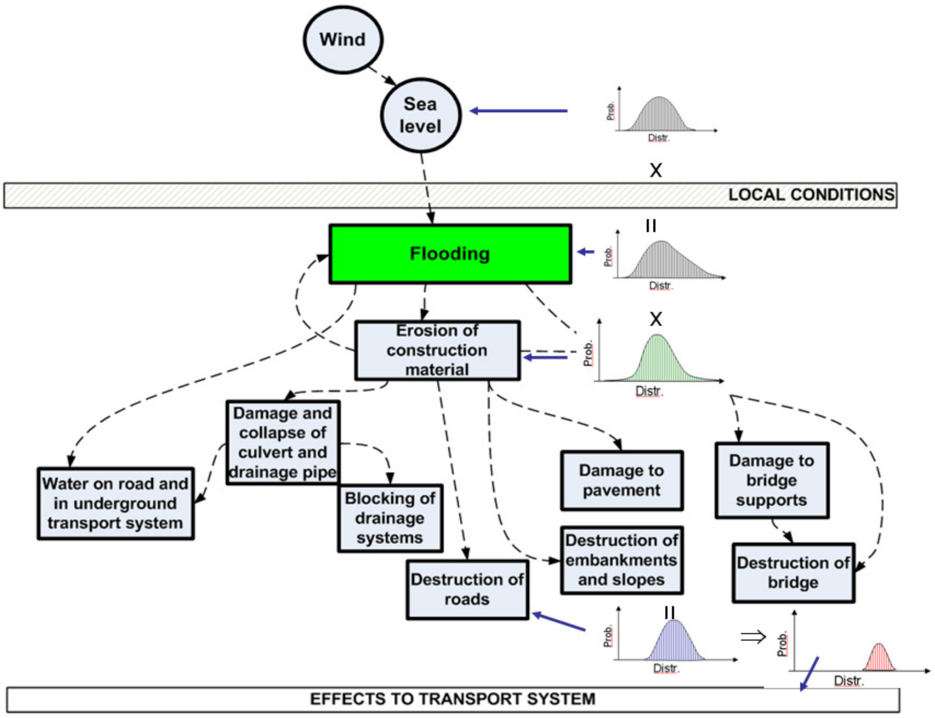


Figure 6. Conceptual map of strong wind and consequent flooding impacts on road infrastructures (source: Makkonen, Törnqvist and Kuusela-Lahtinen, VTT).

Weather impacts on rail transport infrastructure

Snow, low temperatures, wind and their combinations seem to be the most harmful weather phenomena for railway infrastructures (see conceptual map in Figure 7). Snow can block tracks and yards, accumulate on cuttings and damage cables. Low temperatures may freeze switches and other equipment and cause tensional failures in current supply cables. As a result, snow and freezing can forge loss of electricity. Low temperatures also cause load on safety devices, which might get overheated. Freeze-thaw cycles put excess strain on materials and equipment.

Flooding is a severe impact caused by many different phenomena, or their combination. Flooding water damages railway embankments and slopes and scours bridge supports and other structures. Scouring can eventually lead to destruction. Excess water can end up flooding railway tracks or underground structures.

Strong wind or tornadoes can block tracks with fallen trees and debris. Risks during a storm also include damage from lightning to current supply, traffic-control apparatus and safety devices.

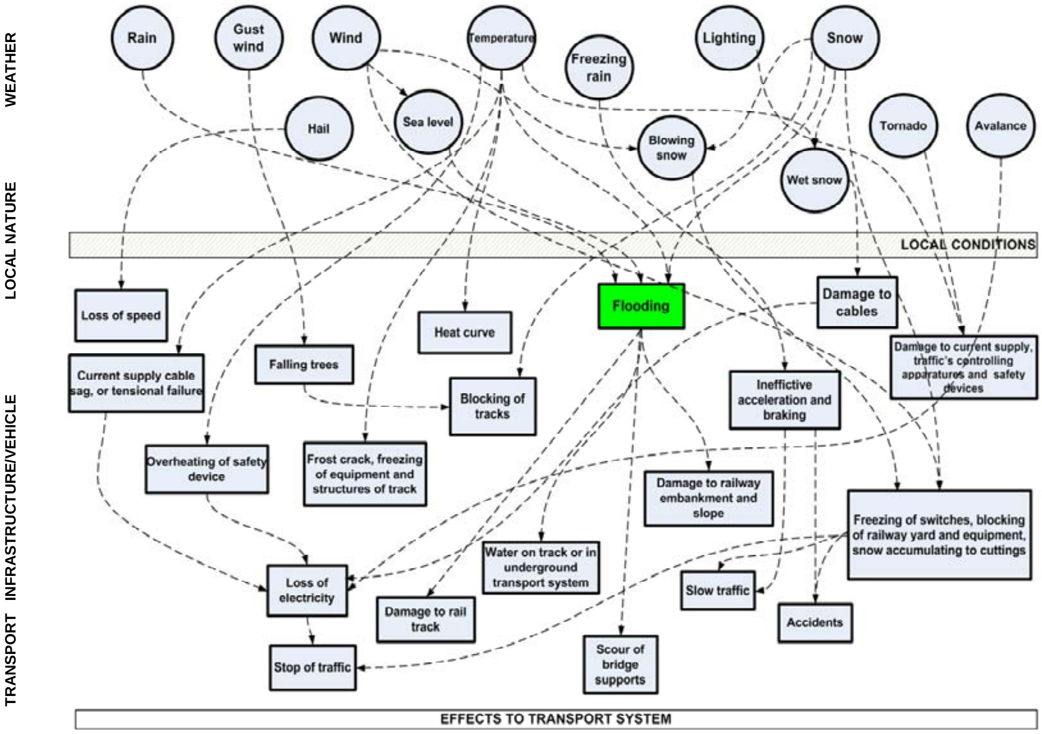


Figure 7. Conceptual map of weather phenomena impacts on rail infrastructure and transport (source Makkonen, Törnqvist and Kuusela-Lahtinen, VTT).

3.2.4 Walking and cycling

According to the literature, the most harmful weather phenomena for walking and cycling are the following: Strong wind, (strong) precipitation, very low or high temperatures and wintry snow and ice conditions (e.g. Koetse and Rietveld, 2009; Aschan et al., 2009). In wintertime, walking and cycling surfaces might be covered in ice, snow, slush or frost. These conditions often result in slipperiness of roads or pedestrian surfaces, causing slipping and falling accidents among pedestrians and cyclists. Slipping accidents occur mostly to inadequate grip between footwear (bicycle tyre) and underfoot (tyre) surfaces. In general, slipperiness is defined quantitatively as a coefficient of friction between surfaces, which is a measurable physical quantity.

The Finnish meteorological institute has identified three cases *(http://ilmatieteenlaitos.fi/liukkaus-ja-jalankulkusaa)* in which surface conditions for pedestrians and cyclists are extremely slippery. They are: (1) when it snows onto the existing ice cover, (2) when it rains or snow melts onto the existing ice cover, and (3) after a heavy snowfall with temperatures at or just below 0°C. Typical falling and slipping accidents cause injuries to the head, elbows and hips of pedestrians and cyclists. Based on a Finnish survey (Penttinen et al., 1999), the highest accident rates for walking and for road transport in Finland have occurred on different dates.

In Finland, about 2/3 of slipping and falling accidents that lead to serious consequences (ca. 70 000/yr) (Grönqvist, 1995; Penttinen et al., 1999) occur outdoors on streets, walkways and in courtyards (Vuoriainen et al., 2000). Around 2/3 of these accidents occur when the walking surface is covered by ice or snow (Grönqvist, 1995). Similarly, it has been noted in Sweden that among elderly persons aged 60 or over who had been injured in the traffic environment, 2/3 of falls involved slipping on ice and snow (Sjögren and Björnstig, 1991). All in all, the socio-economic losses of falling accidents because of slippery pedestrian and cycling paths are huge, more than 2 billion euros per year in Finland alone (Hautala and Leviäkangas, 2007).

Slipping and falling accidents due to wintry snow and ice conditions have been reported in some Nordic and European countries and in Japan (e.g. Björnstig et al., 1997; Gard and Lundborg, 1994; Haslam and Bentley, 1999; Merrild and Bak, 1983; Shintani et al., 2002).

The extreme weather conditions may also affect mode choice decisions, e.g. the distribution between public and private transport in commuting. However, it seems that the ultimate impact of weather on mode choices is rather small.

3.2.5 Aviation – passenger, freight, terminal operations

Weather is and will continue to be a critical factor in aviation operations. The safety and efficiency of flight in general is most influenced by weather events. “No other industry is more sensitive to weather than the aeronautical industry. In spite of our improved ability to observe and forecast the weather to a greater degree of accuracy than ever before, adverse meteorological conditions continue to severely impact the operational safety and efficiency, as well as the system’s capacity.” (Sprinkle and Macleod, 1991). The authors continue: “The impact of severe weather and Instrument Meteorological Conditions (IMC) reaches far beyond the commercial aircraft in the sky. It reaches down into airline scheduling, airport management, cost control, and passenger convenience. For the smaller general aviation fleet, it may mean cancelling the flight, which may have been for business or recreational purposes.”

Therefore, in aviation, the term “extreme weather” may apply already to weather situations in which the surface-based transport sectors still run unaffected.

Weather impacts aviation in terms of safety, efficiency and capacity. There is a positive correlation between safety and efficiency in aviation weather awareness. Technologies aiming at improving safety will also meet the requirements for increasing capacity or efficiency. The simple reason for this is the common source for risks and delays: insufficient weather hazard awareness.

The methods to assess the weather impact on aviation include (Theusner and Röhner, 2006):

- The analysis of weather-related accidents and incidents, with respect to:
    1. Type and strength of weather hazard
    2. Geographical and seasonal distribution
    3. Type of aircraft affected
    4. Typical conditions of occurrence.
- A climatology of weather hazards as part of a risk analysis, with the latter defined by
    - v. Observed occurrence, e.g. of CB
    - vi. Necessary and sufficient conditions for the existence of the hazard, or
    - vii. By issued warnings.

A risk, or the probability of occurrence of an accident, may be defined as the probability of the weather hazard occurrence times the flight frequency times the encounter severity (which includes improper reaction to the hazard encounter).

Weather is the single largest contributor to delays. Quantitative studies of the impact of weather on efficiency are, however, still limited to case studies and are confined to either certain aspects of the problem or to specific countries. Most of these studies are accomplished in the U.S., but in the past 5 years some case studies have also been done within Europe.

Theusner and Röhner (2006) investigated aviation weather hazards, aviation weather impact areas and evaluation methods in the framework of the European Integrated Project FLYSAFE (http://www.eu-flysafe.org/). Most findings collected here are based on their report.

Critical weather phenomena having an impact on efficiency and safety of air traffic are (see e.g. http://www.skybrary.aero/index.php/Weather):

- Thunderstorms and lightning
- Low visibility, associated with cloud, mist, fog, snow or sand storms
- In-flight icing, ground icing
- Wind, gusts and wind shear
- Heavy precipitation including snow and ice as well as surface contamination (standing water, ice, or snow on take-off, landing and manoeuvre surfaces)
- Turbulence (in clouds or clear air)
- Volcanic ash
- Sandstorms
- Aircraft wake vortices.

These phenomena generally reduce the safety margins and favour the occurrence of incidents and possibly accidents. Simultaneously, the capacity of airports is reduced by increasing separation between aircraft, additional holdings or by closing one or even all runways. As a result, the capacity of airports or a particular section of airspace is reduced with delays, diversions and cancellations of flights as a consequence for the passenger.

Generally, weather impact differs for the various phases of flight with immediate effects during take-off and landing. Typically, wind shear, fog, heavy snowfall and low visibility affect the latter ones, while, for example, clear air turbulence is a characteristic en-route hazard. Basic characteristics of an airport such as orientation of runways, capacity, precision landing equipment, topography and local weather phenomena make it susceptible to specific weather hazards. As a consequence, each airport has to be investigated separately with regard to its susceptibility to adverse weather.

Most of the weather related accidents occur during take-off or landing, because (i) some weather hazards such as downdraughts, heavy rain or snow, hail, and wind shear are found predominantly in the lower atmospheric levels and (ii) weather hazards in that last flight phase are not able to be circumvented, due to the necessity of having to land at a certain location and on a runway in a given direction. Moreover, visibility and a minimum cloud ceiling, as well as certain crosswind maxima are required for a safe landing and/or takeoff. During take off, approach and landing the aircraft has to fly slowly in order to operate within the runway and this requires the use of relatively high angles of attack. Therefore the margin to stall is at the lowest during these phases of the flight.

Thunderstorms

Within thunderstorms (cumulonimbus clouds, Cb) areas of microbursts (also called downdraughts), strong wind shear, turbulence, icing, heavy rain, lightning strokes and hail exist simultaneously in the same place or close by. All of these phenomena are a possible threat to aircraft as they can alter the aerodynamic state of flight, damage the hull or engines of the aircraft or cause malfunctions of the on-board equipment. The features of the hazardous elements of a thunderstorm are explained below.

Lightning strokes

Airport ground operations have to be terminated when a lightning strike has been observed within a radius of 5 km around an airport.

With flight experiments it has been found that most lightning strikes to aircraft are triggered by the intrusion of the aircraft into a region of the thunderstorm where the electrostatic field is sufficiently large. The current and the electric field variation measured on the aircraft during the lightning process have enabled the severity of an aircraft strike to be characterised. There are two types of lightning strike to an aircraft. The most frequent case (90% of events) is lightning triggered by the intrusion of an aircraft into a region of an intense electrostatic field. The other case may be the interception by the aircraft of a branch of natural lightning.

Microbursts

Microbursts can be an extreme hazard to aircraft during the landing and take off phases of flight, see Figure 8. An aircraft flying through a microburst may experience extremely hazardous airspeed and lift fluctuations. Although the downdraft from a microburst can be dangerous to an aircraft, the greatest threat comes from the change in wind direction – commonly called wind shear – near the centre of the microburst, which may result in a corresponding loss of airspeed.

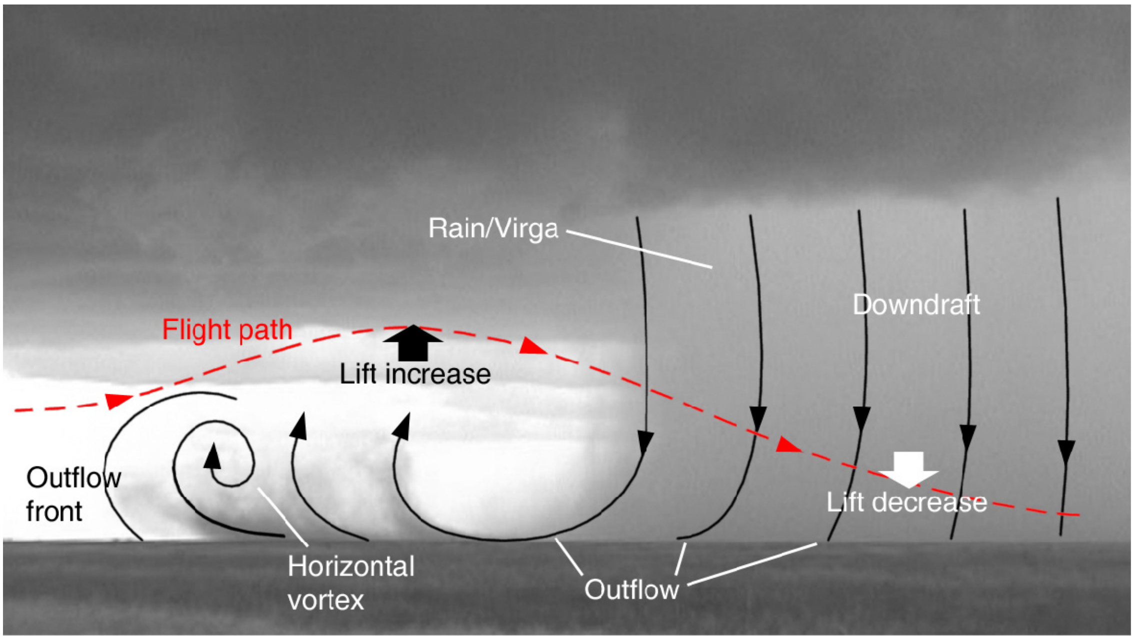


Figure 8. A downdraught or microburst with its typical features and impact upon the flight path. (compiled by M. Theusner)

Microbursts normally cover an area of approximately 2 nautical miles in diameter, although the area of resulting high winds, created when the microburst hits the ground, can be much higher. Winds of up to 130 knots may result when a microburst is formed. Radar meteorologists have defined a microburst as a divergent low-level wind field with a velocity change of at least 7.7 m/s over a distance of between 1 and 4 km. The microburst exhibits severe, low-altitude wind-shear gradients that are experienced by a landing aircraft as rapid changes in the relative wind vector, sometimes to an extent that the performance capabilities of the airplane are exceeded, which results in ground impact. Roughly half of microbursts, as defined by radar meteorologists, are truly hazardous to aircraft (Chambers, 2003).

Microbursts typically occur in the vicinity of thunderstorms when the surrounding air is dry. In general, the dry air causes the rain from the thunderstorm to evaporate. The process of evaporation cools the dry air, which then becomes heavier than the surrounding air. When the microburst reaches the surface, it spreads out from the point of impact in what is referred to as a density current. Most microbursts last for a few minutes, generally less than 10. Microbursts can occur anywhere under convective weather conditions (thunderstorms, rain showers or virga). Virga is rain that evaporates before it reaches the ground and is associated with a “dry” microburst. The terms “microburst” and “wind shear” are often used interchangeably because the vast majority of dangerous wind shears result from microbursts.

Severe wind shear is a rapid change in wind direction and/or velocity and causes horizontal velocity changes of at least 15 m/sec over distances of 1 to 4 km, or vertical speed changes greater than 2.5 m/s.

A gust front is formed along the leading edges of large domes of rain-cooled air, which is a result of cold downdrafts coming from individual thunderstorm cells. At the leading edge of this gust front, a dynamic clash occurs between the cool out-flowing air, the density current and the warmer thunderstorm inflowing air, and produces the familiar wind shift, temperature drop and gusty winds that precede a thunderstorm (Chambers, 2003).

Icing

Icing of the body, the outer skin, air intakes, bend, carburettor sensing devices (Pitot tubes) or the air conditioning of an aircraft can have an impact on its flight characteristics and lift/drag characteristics, as well as on the functionality of certain components, like the engine.

Ice accretion can be defined as (i) the freezing of supercooled liquid cloud droplets after impacting the cold surface of an aircraft, (ii) liquid drops freezing on the supercooled aircraft, or (iii) the accumulation of solid particles like snow flakes and ice crystals. Ice formation by adiabatic cooling of moist air in air conditionings or carburettors of piston engines is rarely observed. That is also the case for overnight hoar frost formation on grounded aircraft, which can also occur when the aircraft quickly leaves a cold air mass. Additionally, there is a whole range of scenarios that provoke icing of turbine blades on the ground. On the whole, icing is distinguished into in-flight icing and ground icing.

Icing is observed in the atmospheric temperature range of -40°C to +6°C (carburettor icing can occur at positive air temperatures due to expansion and subsequent cooling of air). Freezing of supercooled droplets on the frame of the aircraft occurs when it flies through supercooled clouds (in-flight icing). In such a case, cloud droplets with diameters of approximately 20 µm or drizzle drops (50–500 µm) or rain drops (> 500 µm) impact the aircraft and freeze. Drizzle drops are also called supercooled large drops (SLD). Freezing rain originates from raindrops which fall through a supercooled layer of air and impact the aircraft. If such a layer of air is situated on the ground as well, all runways and airport buildings and structures are affected. Freezing rain formation is also known as classical formation and is easier to forecast than freezing drizzle.

The special risk emanating from freezing drizzle is, on the one hand, that the atmospheric conditions leading to its occurrence are not well known (thus, non-classical formation) and, on the other hand, that aircraft are only tested for average drop sizes of up to 50 µm (FAA, 1999). Though aircraft comply with international admission regulations, they are not necessarily qualified for all types of clouds. SLD therefore pose a special risk. Furthermore, they do not freeze on impact on the stagnation point of, for example, the leading edge of the wing (like the 20 µm sized cloud drops), but they remain liquid long enough to flow across the wing for up to 1 m and freeze there. In-flight icing mainly affects turboprop and small aircraft. There are two reasons for that. Firstly, small aircraft usually cannot climb high enough to fly above the clouds and, therefore, spend most of their flight time inside the clouds. Secondly, ice can only be removed pneumatically; so-called rubber boots are used to remove ice accretions. Such a system consumes less energy than thermal ones, which melt away ice using hot exhaust gases and are only used by large aircraft. The rubber boot systems have the drawback that they can only be used when ice has already accreted on the wing.

Turbulence

Even though turbulence is seldom damaging to modern aircraft, which are designed to withstand its stresses, it is the leading cause of in-flight injuries among the flying public. In non-fatal accidents, in-flight turbulence (2/3 are convective, CAT, wake/other) is the leading cause of injuries to passengers and flight attendants. Turbulence-related injuries cost the airline industry over $100 million per year. Whereas turbulence that is triggered by convective processes occurs within or in the vicinity (below, above) of clouds and hence, can be “seen”, there is currently no effective warning system for clear air turbulence.

Atmospheric turbulence is a significant safety issue and is one of the FAA’s organization strategic goals. Using 1983–1997 data from an independent National Transportation Safety Board analysis, statistics revealed that 65 percent of weather-related injuries on U.S. commercial airlines were caused by turbulence. Costs attributed to turbulence were reported at $100 million per year. What was most alarming was that only 35 percent of the turbulence encountered had been forecast (Kirchoffer and Fellner, 2003). In June 1995, the FAA issued a public advisory to airlines urging the use of seat belts at all times when passengers are seated as a precaution against unexpected turbulence (FAA, 1997).

The number of turbulence accidents per million departures (US carriers) has increased markedly between 1982 and 2003 (FAA, 2005) and cannot be explained by the increase in air traffic volume alone. Instead, load factors might be a controlling factor.

Convective Turbulence

Convective turbulence is a phenomenon found throughout the troposphere in the presence of convection of varying strength. It can be found in the planetary boundary layer (the lower few hundred metres of the Earth's atmosphere) where it is particularly dangerous as the aircraft usually is in the stages directly prior to landing or directly after take-off, and are flying at low speeds (risk of stalling). Any turbulence-enforced change in altitude therefore bears the risk of collision with terrain.

In mid-level shower clouds and shallow convection, turbulence usually does not pose a serious risk to the aircraft itself. It does, however, reduce the flight comfort of the passengers and may even lead to serious injuries, if no seat belt is worn, which is usually the case for cabin attendants. The typical up- and downdraft speeds are of the order of up to ±5 m/s.

The real threat to aircraft is convective turbulence found in thunderstorms. There, updrafts of up to +65 m/s and downdrafts of -25 m/s can exist in close proximity. The strong wind shear and turbulence induced by these drafts is a serious safety hazard for passengers and also the structural integrity of aircraft. Turbulence can not only be found within the convective systems, but can induce CIT/CAT (see below) far away from the originating systems through the excitation of gravity waves at inversion layers.

Three levels of turbulence can be distinguished: light, moderate, and severe. Conditions inside the aircraft in light turbulence include: liquids are shaking but not splashing out of cups, carts can be manoeuvred with little difficulty, and passengers may feel a slight strain against seatbelts. Conditions inside the aircraft in moderate turbulence include: liquids are splashing out of cups, carts are difficult to manoeuvre, it is difficult to walk and to stand without balancing or holding on to something, passengers feel a definite strain against seatbelts. Finally, conditions inside the aircraft in severe turbulence are: items falling or lifting off the floor, unsecured items are tossed about, food service and walking is impossible, passengers are forced violently against seatbelts.

Clear-air turbulence, CAT

Layers of turbulence without the presence of clouds at high altitudes (usually above 4500 m) are referred to as clear-air turbulence (CAT). CAT is mostly caused by strong wind shear in the vicinity of the jet streams, but also by breaking gravity waves above mountain ranges and above convective weather systems (e.g. thunderstorms). Its sudden appearance in an otherwise calm and clear atmosphere is mostly a safety and convenience problem for passengers. Nevertheless, CAT can also become a safety problem for the structural integrity of the aircraft, for example if inappropriate movements of the elevators or rudders are conducted. Turbulence also leads to frequent load alternation and, consequently, to structural loads with resulting material fatigue.

CAT around jet streams is of importance to meteorology and to the aviation industry (Pepler et al., 1998). Turbulence is generated in regions where the Richardson number, Ri (the static stability divided by the square of the wind shear) falls below 0.25 (Scorer, 1987) and is therefore preferentially found on the flanks of jet streams where the wind shear is large. In upper-level fronts, turbulence has, among others, two important consequences: first of all it provides a source region for short-period gravity waves which can propagate into the middle of the troposphere (VanZandt et al., 1979; Fritts and Nastrom, 1992) and cause CAT there. Secondly, it manifests in upper-level fronts that form beneath northerly jet streams, which frequently display folded tropopauses (Danielsen, 1968; Danielsen et al., 1987; Shapiro et al., 1987; Vaughn et al., 1994), again resulting in additional CAT. Observations of turbulence around jet streams by specially instrumented aircraft have confirmed the preferred location of turbulence in the shear zones above and below a jet, but they also showed that the turbulence is patchy and intermittent, and differs considerably from one jet to the next (Pepler et al., 1998).

Other investigations show that a jet stream alone is not enough to cause severe turbulence, but that the presence of moist convection (e.g. mesoscale convective systems, super cells or other strong convective systems) in the vicinity of a jet stream dramatically increases the risk of encountering CAT. Kaplan et al. (2005) analysed 44 cases of severe turbulence environments associated with commercial aviation accidents. They found a prevalence of severe accident-producing turbulence within the entrance region of the polar or subtropical jet stream at the synoptic scale. Hence, the presence of moist convection, jet stream curvature, upward vertical motion and cold air advection seem to be good indicators for the occurrence of severe CAT.

Volcanic Ash Over Europe[1]

On a global scale, more than 1500 volcanoes are considered potentially active. In Europe, volcano related impacts on society, by various volcanoes of different compositions, tephra dispersals, explosivity, and recurrence intervals, have been reported. The effects include destructions in the near field as well as in the far field. The volcanoes are located in Iceland (e.g. Katla, Eyjafjallajökull, Hekla, Krafla), Spain (e.g. La Palma, Tenerife, El Hierro), Portugal (Azores), Italy (Vesuvius, Campi Flegrei, Etna), Greece (Nisyros, Santorini), and Turkey (e.g. Kula, Arrarat, Nemrut Dagi). Volcanism in Germany (Eifel) and in continental France (Massif Central) is considered geologically likely, although not reported historically, hence being highly uncertain.

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[1] Major parts of this text have been taken from the German contribution to a Draft Report for Guidelines (Klatt, P. 2010: Volcanic Ash Cloud Experts Group. German input for the preparation of the 1st draft report, Version 2, April 2010) and from Wikipedia (http://en.wikipedia.org/wiki/2010_eruptions_of_Eyjafjallaj%C3%B6kull)

Volcanic ash is a major hazard to aircraft. Smoke and ash from eruptions reduce visibility for visual navigation, and microscopic debris in the ash can sandblast windscreens and melt in the heat of aircraft turbine engines, damaging engines and making them shut down. The presence and location of the ash plume depends upon the kind of the eruption (intensity, emission heights, duration and emitted material) and the prevailing winds at the level of the emission heights and below.

The eruption of the Eyjafjallajökull volcano in 2010 was a continuous sequence of volcanic events that started on 20 March 2010. The first phase of the eruption was an effusive eruption that did little damage. However, on 14 April 2010 the eruption entered an explosive phase and ejected ash to heights in excess of 9 km.

The combination of several factors made this volcanic activity so disruptive to aviation:

- The volcano’s location was directly under the jet stream, which was unusually stable at the time of the eruption’s second phase (14th of April), maintaining a continuous south-easterly heading.
- The second eruptive phase took place under 200 m of glacial ice. The resulting melt water flowed back into the erupting volcano, where the rapidly vaporising water significantly increased the eruption’s explosive power and the erupting lava cooled very rapidly, creating a cloud of highly abrasive, glass-rich ash.
- The volcano’s explosive power was sufficient to blow ash into large altitudes and thus directly into the jet stream.

While some ash (typically the largest particles) fell on uninhabited areas in Iceland, most of the lighter material was carried away by westerly winds. In response to concerns that ash ejected by the volcano would damage aircraft engines, the controlled airspace of many countries in Europe was closed, resulting in the largest air traffic shutdown since World War II. With large parts of European airspace closed to air traffic, many more countries were affected as flights to and from Europe were cancelled. No commercial aircraft were damaged.

After an initial uninterrupted shutdown over much of Northern Europe from 15 April to 23 April, airspace was closed intermittently in different parts of Europe in the following weeks, as the path of the ash cloud was tracked. The ash cloud caused further disruptions to air travel operations in Ireland, Northern Ireland and Scotland on 4 and 5 May and in Spain, Portugal, northern Italy, Austria and southern Germany on 9 May. Irish and UK airspace closed again on 16 May and reopened on 17 May. The International Air Transport Association (IATA) estimated that the airline industry worldwide would lose €148 million (US$200 million, GB£130 million) a day during the disruption.

In order to respond quickly to an eruption with respect to aviation, reliable data from volcanology, atmospheric sciences and aircraft engineering must be available beforehand or with very short delays (timescale of hours to 1 day) after eruption. Additionally a network with a liberal data exchange and communication policy has to be developed to support participating collaborators and globally connected scientists.

From a volcanologic point of view one has to monitor the potentially active volcanoes and provide early warnings, to estimate the volume flux, and to identify the ash and the gaseous exhaust. An ash composition and dispersion database needs to be collected, and their effects on air traffic (in particular on the jet engines) to be studied. Due to melting temperature ranges from 600–1200°C, some volcano ash compositions may pose significant risk to airplane safety, while others do not. Research is needed to weigh up the potential hazards and risks for each volcano.

Since the early 1980s it has been well known that volcanic ash is a dangerous threat for aviation. Volcanic ash in high concentrations may lead to immediate engine failure. Since then a general rule has been established by aircraft and engine manufacturers that aircraft operation in areas with a measurable content of volcanic ash in the atmosphere is not permitted. This led to the closure of almost the entire European air space in April 2010. It is evident that acceptable ash concentration limits and adequate inspection requirements have to be established in order to be better prepared for future events.

In order to allow a controlled continuation of civil air traffic under conditions where parts of the air space are contaminated with volcanic ash, the following information has to be available:

Operations

- Online information about the current 3D distribution of volcanic ash in the relevant air space (concentration, particle size, chemical composition and ash-type including melting point).
- Validated computer models and sufficiently accurate 24-hour 3D forecast and at least hourly updates validated by 3D measurements.
- Online availability of quality-checked and approved measurements and forecasts to flight safety organizations, airports and operators.
- Real time information about closed air space and flight levels prohibited for cruise, 3D flight trajectory optimization with respect to minimum ash concentrations.

Engines

- Acceptable accumulated ash ingestion limits for all engine types, adequate understanding of short-term effects (immediate engine failure), and long-term effects (erosion, ash deposits on turbine vanes and blades, plugging of cooling holes and insufficient cooling of hot gas components due to particle deposits within the engine cooling system and the secondary air system).

- Derivation of thresholds for the ash mass concentration density (concentration per flight km).

Atmospheric sciences

- While on-board aircraft weather radars can detect clouds via the hydrometeors, a dry volcanic plume is invisible to the on-board radar systems. Therefore data must be obtained by specialised in-situ measurements (e.g. by aircraft measurements), airborne lidar measurements in addition to satellite and ground based lidar measurements at specific stations.
- In order to apply the meteorological forecast and plume dispersion systems, near real-time information on plume distribution including size resolved particle distribution and possibly structure over large areas are needed. By using these data for assimilation or validation, quality assured atmospheric and plume dispersion modelling will provide the required information for aviation operations.

3.2.6 Inland waterway shipping operations and infrastructure

Similarly to other modes of transport, inland waterway transport has to deal with weather events affecting navigation conditions and the infrastructure on inland waterways. Most significant extreme weather events result from high precipitation, droughts as well as temperatures below zero degrees. Heavy rainfall, in particular in association with snow melt, may lead to floods resulting in suspension of navigation and causing damage to the inland waterway infrastructure as well as the property and health of human beings living in areas exposed to flooding. Long periods of drought may lead to reduced discharge and low water levels limiting the cargo carrying capacity of vessels and increasing their sailing times, in particular, when sailing downstream, and temperatures below 0°C over a longer period may cause the appearance of ice on waterways leading to suspension of navigation and possible damage of infrastructure, e.g. buoys.

The following gives a preliminary overview of the impacts of extreme weather events on inland waterway transport and infrastructure in the EU. The most significant European inland waterways are shown in Figure 9 and are located in the North-South corridor, the Rhine corridor, the South-East corridor and the East-West corridor. The focus is on the Rhine-Main-Danube corridor, where highly important inland waterways such as the Rhine, the Main, the Main-Danube canal and the Danube are located (Figure 10). In this corridor a variety of different geographical, meteorological and hydrological domains are present, as well as the highest amount of cargo on inland waterways, allowing for a comprehensive consideration of the topic.

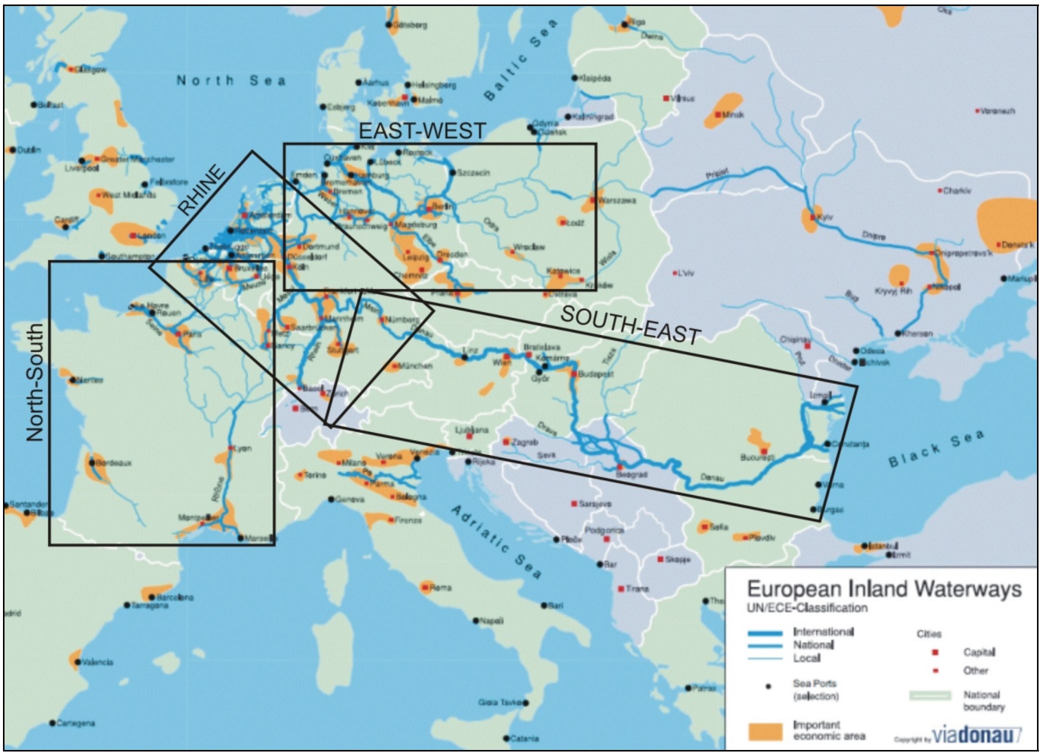


Figure 9. Overview of European inland waterways. Source: via donau.

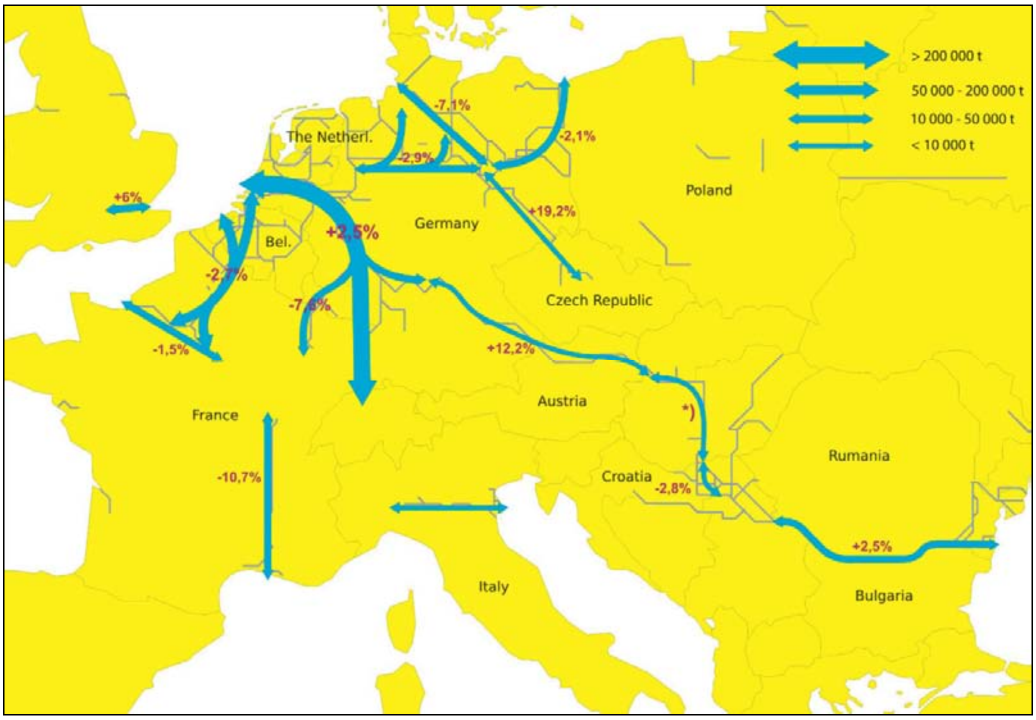


Figure 10. Transport flows on European inland waterways in 2007. Numbers in tons should be multiplied by 1000. Source: CCNR, 2009.

The key meteorological parameters influencing navigation on inland waterways are precipitation and air temperature (PIANC, 2008). These parameters determine the water supply and the water temperature in the navigable river sections. Changes, especially in the water supply, will alter the occurrence of extreme hydrological conditions, changing the navigability of waterways as well as affecting the river morphology and the waterway infrastructure. Changes in water temperature have mainly an impact on the presence and absence of ice, also affecting navigability and the waterway infrastructure.

Drivers and impacts on inland waterway transport

According to PIANC (2008), the drivers having an impact on inland waterway transport and the infrastructure are water supply, water temperature, river morphology and changes in ice cover (Table 4). Also worth mentioning are strong winds and limited visibility.

Table 4. Drivers and impacts on inland waterway transport. (PIANC, 2008)

Drivers	**Impacts**	**Rivers, channels canals, lakes**	**Locks, dams, infrastructure**	**Operational control**	**Vessels**
Water supply: increased precipitation Extreme conditions: more extreme floods	Increased water level and velocity	x	x	x	x
	Changes in sedimentation processes (bank failure, local scour, locations of aggradations and degradation)	x	x	x	
	Manoeuvrability		x		x
	Increased loads on structures		x		
	Less development land area available		x		
	Reduced regularity of the port		x	x	
	Reduced capacity of natural systems to recover	x			
Water supply: decreased precipitation Extreme conditions: more extreme droughts	Decreased water level and velocity	x	x	x	x
	Reduced regularity of the port		x	x	
	Changes in sedimentation processes (locations of aggradations and degradation)	x	x	x	
	Reduced capacity of natural systems to recover	x			
Water supply: changes in form and quantity of seasonal precipitation	Change in timing of seasonal high and/or low water	x	x	x	x
	Changes in sedimentation processes (locations of aggradations and degradation)	x	x	x	x
Water temperature	Ecosystem impacts affecting habitat	x		x	
	Oxygen depletion	x		x	
	Reduced capacity of natural systems to recover	x			
River morphology	Changes in sedimentation processes (locations of aggradations and degradation)	x	x	x	x
	Ecosystem impacts affecting habitat and lifecycle				
	Reduced capacity of natural systems to recover	x			
Changes in ice cover	Shorter duration of river ice	x	x	x	x
	Changes in location of ice jams	x	x	x	

Water supply

Changes in water supply due to increased and decreased precipitation and changed evapotranspiration lead to increased and decreased water levels and velocities, and resultant changes in sedimentation processes such as bank failure, local scour, and locations of aggradations and degradation. Changes in water levels that impact the movement of sediment, and hence channel maintenance activities, will require increased or decreased dredging, depending on the locations and specific impacts.

Changes in water level and velocity can also impact manoeuvrability and operational efficiency of navigation structures. Navigation structures may also experience loadings different from design loading, affecting stability and resiliency. Higher water levels could require modifications to existing ports and mooring areas or reduce their potential for expansion.

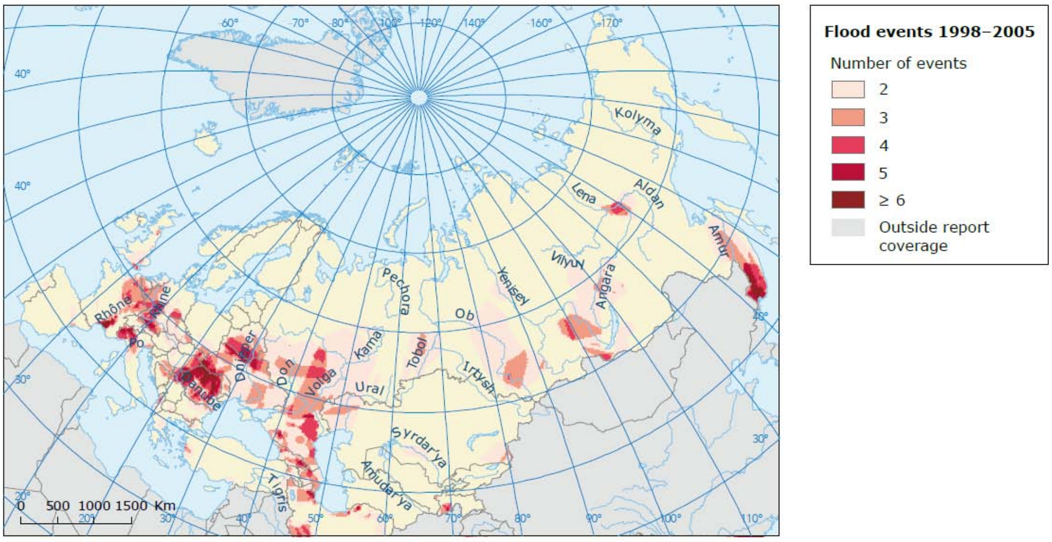
Changes in the timing of seasonal high water and seasonal low water may impact shipping and maintenance schedules. These issues are already being observed in the North American Great Lakes, where falling lake levels due to changes in precipitation reduces ship clearance in channels and harbours and increases demand for dredging (Kling et al., 2003).

The occurrence of high water is usually a result of long lasting heavy precipitation (rain or rain and snow), snow melt, or a combination of snow melt, precipitation and ice jams in the case of winter high water or winter floods. The criteria applied for evaluation of the severity of the high water situation and its effect on transportation and the inland waterway infrastructure are related to the water levels of the waterway. The most relevant ones are the Highest Navigable Water Level (HNWL), the 30-year level of return of high water (HWL30), and the 100-year return level of high water (HWL100).

In general, the consequences of high water may be suspension of navigation, delays, vessel damage due to driftwood (e.g. propulsion devices), modification of river and bank morphology, possible severe damage to as well as clogging or sedimentation of navigation signs, gauges, ramps and stairs, berths, banks, towpaths, port and lock areas, dams, groins and training walls as well as catastrophic flooding of protected areas. The consequences of high water, in particular of flooding, are in general more severe to the waterway infrastructure and protected areas than to waterway transport itself. Suspension of navigation due to high water usually accounts for only a few days in a year. However, significantly longer periods may also appear depending on the waterway under consideration.

In Europe, critical weather constellations leading to significant high waters occurred in August 2002, July and August 2005 and January 2004. In January 2003 on the Elbe the occurrence of ice led to ice jams, resulting in combination with winter precipitation to critical high water situations (Internationale Kommission zum Schutz der Elbe, 2005).

Figure 11 gives an overview of river catchments affected by flooding between 1998 and 2005. It shows that the Danube from the Black Sea to the Hungarian border and the Rhine-Main-Danube corridor to the border of Austria are vulnerable to flooding.



Source: EEA, based on Global Active Archive of Large Flood Events, Dartmouth Flood Observatory — EMDAT.

Figure 11. River catchments affected by flooding during the period 1998–2005 (EEA, 2007).

Low water situations are not unusual for inland waterway transport, and the inland waterway transport system is able to cope with such situations.

In general, low water results in a reduced cargo carrying capacity of vessels as these may not be loaded fully due to limited water depth. The reduction of the cargo carrying capacity depends on vessel size. Large vessels are affected more strongly than small vessels, and may become less economical in extreme low water situations than smaller ones. However, under normal water conditions larger vessels are more economical due to the law of scale. Whether a low water situation is becoming an obstacle to transportation has to be evaluated separately for each vessel under consideration. For a typical large motor cargo vessel on the Danube, a reduction of ship draught by 10 cm results in a reduction of the cargo carrying capacity by approximately 100 tons.

Apart from the fact that the cargo carrying capacity is reduced, low water may cause an increase of power demand when sailing at unchanged speed or a speed reduction when no additional power is available due to the shallow water effect on the flow field around the vessel. Consequently, the fuel consumption will increase and the sailing times will become longer, leading to delays and fewer round trips. Further, the manoeuvrability of vessels will become poorer due to the shallow water effect, increasing the risk of accidents such as collisions.

Water temperature

Changes in water temperature are expected to affect navigation primarily through regulations to protect and enhance riverine and estuarine ecosystems. Warmer water temperatures, resulting in an increased occurrence of oxygen deficits for the same nutrient loading, will adversely impact these ecosystems. Since oxygen deficits are often compensated by discharging water over spill weirs, the water depth in navigable rivers could be reduced.

River morphology

Changes in sediment load cause changes in river bed erosion and river dune development, as well as changes in floodplain sedimentation, and therefore require an adaptation of sediment management, i.e. dredging or artificial sediment supply. Changing erosion, scour, and sedimentation patterns also impact ecosystem structure and functioning.

Changes in ice cover

The occurrence of ice on inland waterways is not necessarily a serious phenomenon. However, once the ice cover becomes so thick that inland waterway vessels can no longer travel, the impacts on the transport system may be severe as navigation has to be suspended, sometimes for many weeks. It is important to note that not all waterways are affected by the occurrence of ice. E.g. on the Rhine navigation has not been suspended due to ice since the 1970s. Vulnerable to ice occurrence are waterways with low flow velocities and canalised sections where locks are present, e.g. the Main-Danube Canal. The occurrence of ice may lead to ice jams resulting, in combination with winter precipitation, in critical high water situations or even in floods as occurred in January 2003 on the Elbe (Internationale Kommission zum Schutz der Elbe, 2005). The occurrence of ice may damage navigation signs, leading to reduced safety of navigation, but also the waterway infrastructure e.g. locks may no longer be operated due to ice jams clogging the lock area or due to frozen moving parts. On the Upper Danube a severe ice situation develops roughly every 10 years, but is expected to become less severe as a result of global warming and warming of the water in the Danube. Although climate trends indicate shorter periods of ice cover, leading to longer sailing seasons, a high degree of variability in local climatic conditions is still expected to cause ice impacts to inland navigation for many years. Warmer early winter air temperatures, followed by a rapid plunge in air temperature, can result in thicker or rougher than normal ice cover formation or freeze up jamming (PIANC, 2008).

Wind

Generally, wind does not constitute a significant obstacle to inland waterway transport. Most inland vessels are sufficiently wide and stable to cope with strong winds. Nevertheless, locally wind speeds may reach values hindering navigation e.g. on the Danube close to the Iron Gates. There, navigation of pushed convoys in ballast without bow thrusters may be suspended. Due to the large wind lateral area of the vessels above the water line, the side forces acting on the vessel may become so high that safe manoeuvring may not be possible using only the propulsion devices of the pusher.

Further, container vessels with open cargo holds may face stability problems due to increased heel and rolling, leading to flooding of the cargo holds; unlashed empty containers located on the upper tiers may start sliding, which has been investigated in detail for a large motor cargo vessel (L = 110 m, B = 11.4 m, T = 3.1 m) by Hofman and Bačkalov (2010). A threshold value for a critical wind speed of 18 m/s was derived, which agrees very well with the value at which the authorities may suspend navigation for certain vessels on the Danube close to the Iron Gates. Interviews with masters of vessels in this area even gave critical wind speeds of 15 m/s.

Critical wind speeds in general may be derived indirectly from Directive 2006/87/EC, which sets limit values for wind pressures in KN/m^2 (e.g. 0.25 KN/m^2) that have to be transformed into wind speeds for each vessel under consideration, leading also to different critical wind speeds for different vessels. Further, the influence of wind is taken into account by a wind coefficient C_{kw} given in t/m^2.

The consequences of strong wind may be interruption of navigation and reduced manoeuvrability of a vessel, leading to delays and increased time for manoeuvring operations as well as possible collisions with waterway infrastructure e.g. when entering locks, requiring increased maintenance. Additionally, open cargo holds may be flooded and unlashed empty containers on upper tiers lost due to sliding, possibly leading to interruption of navigation and to additional actions related to the recovery of lost containers.

Container vessels that are improperly loaded (e.g. empty containers in the cargo hold and loaded containers on the upper tiers) may capsize, although the stability of inland waterway vessels in general is very high due to their relatively large width/height ratio. Recently a container vessel almost capsized on the River Rhine: In 2007, M/V Excelsior suffered from loss of stability and almost capsized due to improperly stored containers associated with an unlucky combination of a turning manoeuvre, wind, current and squat action, leading to the loss of 32 containers and suspension of navigation on the Rhine for 6 days, affecting some 500 vessels (see Figure 12).

Reduced visibility

In the case of reduced visibility due to fog, rainfall, haze, snowfall or other factors, as a general rule all vessels are requested to navigate by radar (CEVNI, 2009). The decision as to whether reduced visibility is present and whether the appropriate steps should be taken is up to the master of the vessel. In the former edition of CEVNI (CEVNI, 2007), in the Specific Requirements under National Regulations a threshold value is given for reduced visibility as visibility below 1 km.

Vessels underway in reduced visibility must proceed at a safe speed as required by the reduced visibility and the presence and movements of other vessels and local circumstances.

Towed convoys must proceed immediately to the nearest safe berthing or anchoring areas if visual signalling between the towed vessel and the motorized vessel is not possible. For towed convoys proceeding downstream, navigation by radar is prohibited. In reduced visibility, vessels and convoys not navigating by radar must proceed immediately to the nearest safe berthing or anchoring areas.

Reduced visibility is not a major obstacle to inland waterway transport; most vessels are equipped with radar, and navigation can proceed in circumstances that are not possible for other modes of transport such as road and rail. However, reduced visibility may require a reduction in speed or even interruption of navigation with resulting delays. In such conditions vessels without radar are not allowed to navigate and are required to stop. Minor impacts of reduced visibility include collisions with navigation signs, which might be damaged, and collisions with the waterway infrastructure.

Figure 12. Floating containers on the River Rhine stemming from the motor cargo vessel M/V Excelsior, which almost capsized due to improper storage of containers and wind, current and squat action during a turning manoeuvre in 2007. Source: DPA – Deutsche Presse Agentur.

3.2.7 Short-sea shipping and harbours – special focus on the Mediterranean and the Baltic Sea

Mediterranean region

Short-sea shipping plays a major role in EU transport and is expected to grow from 2000 to 2020 at a rate of 59% in volume (metric tonnes) (Martinez and Castells, 2006). This growth would most likely be at the expense of other means of transport, such as road transport, because maritime transport offers an environmental edge over the problems of traffic congestion, pollution, noise and accidents. Extreme weather, however, plays a major role in the smooth operation of maritime transport. The objective is to identify and document extreme weather events that affect short-sea shipping in the Mediterranean.

Review of research results

The literature review was performed mainly by a search of the Internet. The search included parameters such as accidents, incidents, delays, closed ports etc. and many other parameters that could be relevant to this study. The results show that scientific articles or databases that document short-sea shipping related issues in the Mediterranean are difficult to find on the Internet. The main source of the Internet search was news-related articles. While it was fairly easy to find news on recent maritime transport incidents, reports on older incidents tend to be stored in archives.

The results of the Internet search are summarized in Case Descriptions. Information is documented in the following categories:

- Weather – Conditions
- Event – Information
- Location (by METAREA as shown in Annex 3)
- Consequences
- URL.

Weather conditions reported in the news articles are mainly storms with winds above 6 BF and fog or sandstorms that reduced visibility. In some cases the results are severe, such as sinking of the vessel and loss of life among the crew. In other cases the consequences are simply delays, which can be interpreted as financial losses.

The Internet search did not reveal any incidents regarding Mediterranean ports, but an excellent guide was found. The European Severe Weather Port Guide, developed by the Naval Research Laboratory in Monterey, California, addresses almost every major port in the Mediterranean and has valuable information such as detailed port information, hazardous conditions for the port in the various seasons, and protective or mitigating measures. The guide is available online: http://www.nrlmry.navy.mil/~cannon/medports/

Extreme weather phenomena

A rough description of the Mediterranean climate would be wet winters and dry summers. In summer the subtropical high-pressure belts move northward towards Europe, and in winter these belts move towards the equator with low-pressure depressions moving in from northern Europe and the North Atlantic. These low-pressure depressions, when associated with strong winds and high waves that affect marine transport, are considered extreme weather events. There are also local winds that are not associated directly with low-pressure depressions, such as the Mistral, Bora and the Etesians that can affect marine transport. Also visibility is very important at sea. Sandstorms and fog are two weather phenomena that can reduce visibility and hence influence marine transport. Although the probabilities of the two latter leading to accidents are not as great as a storm, reduced visibility can cause delays of ships in certain key areas of marine transport which will have financial impacts.

Winds – Waves

The results clearly indicate that strong winds and high waves can have a major impact on short-sea shipping. The severity of the impact clearly depends on the magnitude of extreme weather, i.e. magnitude of the wind and significant wave height (see Appendix 2), but also on the type of vessel and the location of the extreme weather. There are many types of vessels that perform various routes in the Mediterranean, and clearly larger vessels can withstand more severe weather. Hence what is considered extreme weather for certain categories of ships can be considered normal for other ships, making it difficult to identify the extremes (Motte et al., 1994). The same is true with the location of the extreme weather. The same storm can cause different types of problems in different areas, for instance close to shore or outside ports, and in some areas it may cause no problems at all.

Visibility

Fog and sandstorms are two other extreme weather events identified here that can influence short-sea shipping. These phenomena are rather more difficult to forecast than wind speeds and wave heights near storms. This makes preplanning or rerouting of vessels almost impossible, further increasing the impact these extreme weather events have on maritime transport.

Conclusions

The study showed that a database with extreme weather impacts on Mediterranean marine transport is not freely available to research. Although the news articles found during the Internet search are fairly recent and do not provide complete details of the incidents, they nevertheless reveal the extreme weather phenomena and their impacts on short-sea shipping. Strong winds and high waves together with visibility-related phenomena such as fog or sandstorms are the extreme weather phenomena identified here as having negative impacts on short-sea shipping in the Mediterranean. The same phenomena affect the normal operation of Mediterranean ports. The impacts differ depending on the magnitude and location of the extreme weather together with the maritime transport operation itself. Further analysis is required to classify the impacts of extreme weather on maritime transport.

Baltic Sea

The Baltic Sea is one of the most heavily trafficked seas in the world, accounting for up to 15% of the world’s cargo transportation. In addition, there are frequent ferry routes and cruises on the Baltic Sea (HELCOM 2009). Strong winds and high waves affect safety and the economy of marine transport on all seas. However, the following describes some of the adverse weather phenomena characteristic for shipping on the Baltic Sea.

Many of the Baltic Sea ports are icebound in a normal winter. Northern ports in the Gulf of Bothnia are icebound for roughly 6 months and ports along the Gulf of Finland for about 3 months. For example, in Finland there are around 50 international trade seaports, 23 of which are kept open throughout the winter by icebreakers. The inland ports are usually closed to traffic from mid-January to mid-March.

The Baltic Sea countries can set traffic restrictions based on safety aspects for ships sailing in icy conditions (HELCOM 2010). In winter 2009-2010 traffic restrictions were in force for 123 days in the Gulf of Riga, 112 days in the Gulf of Finland, 130 days in the Sea of Bothnia and 157 days in the Bay of Bothnia. A total of 7708 vessels were assisted by icebreakers. The cost of Finnish icebreaking services ranges from 22 to 39 million Euros depending on the severity of the winter. The cost of Swedish icebreaking services varies from 15 to 34 million Euros (BIM 2010).

Ice in the Baltic Sea occurs both as fast ice and drift ice. Fast ice occurs in the coastal archipelago areas. Drift, forced by winds and currents, is dynamic in nature. Ridges and brash ice barriers constitute major obstructions to maritime navigation in the Baltic Sea in winter. Powerful, ice-strengthened vessels can break through thick level ice, but they are not capable of navigating though ridges and heavy brash ice barriers without icebreaker assistance. Ice dynamics cause high pressure in the ice field, endangering vessels and causing time delays of up to several days (Schmelzer et al., 2008).

In certain weather conditions, ice formed from seawater accumulating on the hulls and superstructures of ships can present a serious danger. Ice accumulation may occur from spray or seawater breaking over the ship when the air temperature falls below the freezing point of seawater.

Fog is not very frequent over the open sea but is more common in narrow channels and inlets in winter and spring. Fog is most frequent over the open sea in April and May while the seas are still cold but the air temperature is rising. In March and April, fog frequencies are around 25% near the Southeast of Sweden and near the South of Gotland and 10% elsewhere.

Navigation on the Baltic is restricted by accessible depths of the seabed. The average sea depth is only 55 m. Therefore, atmospheric phenomena like strong winds and air pressure variations can initiate sea level fluctuations, limiting access to certain ports in the Western Baltic (Baltic Master, 2006).

Based on expert interviews in Finland, the most harmful winter conditions for Baltic Sea shipping are periods of mild temperatures complemented by heavy winds and occurring between (long) periods of low temperatures. This kind of alternation creates “slush belts”, which are very difficult to navigate.

3.2.8 Supply chains – reliability under extreme weather conditions

The reliability of the supply chain is the most important quality required from logistics service providers. A high degree of uncertainty means that operators and shippers may adopt costly hedging strategies such as high inventory or reserve levels needed for emergency/crisis management. Recent research suggests that costs induced on the supply chain by reliability sustenance can be much higher than the direct costs of freight transfer and delivery. Thus, logistics operators face a trade-off between the direct costs of freight movement and those arising from securing operational resilience.

Since fulfilment of the logistics reliability warranty affects the competitiveness of both shippers and logistics providers, it can be a reason for certain operators diversifying away from shipments of some time-sensitive goods.

Since reliability is so important for any supply chain, risk management is the key to its sustenance. Supply chains, especially those that span large geographical distances, cut across multiple country territories and/or involve multimodal transport and are exposed to external and internal risks. Causes of external risks may be legion and include both man-made and natural disasters such as extreme weather-induced disruptions. Because internal risk is mostly attributed to the ways in which supply chains are configured, managed, and operate, it can be influenced by managerial actions. This, however, is not always the case with external risk (Christopher, 1998).

The magnitude of external risk is typically exacerbated by the dependence of logistics services on public and private infrastructure such as roads, airports and harbours, rail networks, ICT installations, warehouse and storage facilities, and energy and traction provision whose maintenance and functionality are not supervised by logistics companies.

Management of natural hazard risks

Since management of risks produced by external hazards is usually limited, the main way to deal with these dangers involves adaptation.[2] Adaptation may require certain flexibility or operational slack within the logistics system for dealing with ad-hoc uncertainties and functional disruptions. This flexibility is, however, almost non-existent under the "just-in-time" supply regime where the buffer inventory is removed from production and/or distribution sites while all inputs are held in transit. Because external and internal risks can interact, they may magnify the scale and magnitude of initial hazards.

Since climatic and/or extreme weather-caused events may bring about loss of life, injury, and damage to cargo and production assets (such as rolling stock) thus jeopardising the logistics mission, how the supply chains adapt to these hazards will affect the logistics reliability. Adaptation strategies should take into account how people respond when faced with risks. This, however, could be quite challenging.

Based on the above, it seems appropriate to ask if it is possible to develop general guidance for adaptation to natural and/or weather-induced hazards, beyond the criteria defined by physical standards. If this were feasible, one could simply define the hazard adaption/ mitigation strategies matching a given risk distribution pattern and then apportion an "appropriate" level of resources to a catalogue of actions suitable for dealing with the different disturbances.

Such physical standards are already in use in many cases. Certain activities, such as building of new transport infrastructure and maintaining of the existing one in areas affected by severe thunderstorms, blizzards or in flood-prone regions are subjected to specific regulations reflecting the frequency of hazardous events (Lindgren et al., 2009). Thus, maintenance of road and/or rail infrastructure exposed to risk of slides may also be adjusted to slides occurrence and/or probability of different categories of damaging effects. In Norway, for example, it is prohibited to build new roads in mountain areas prone to earth slides and/or blockages caused by snowstorms and avalanches (Aaheim et al., 2009).

Any adaptation strategy will require contingency plans reflecting the scope and the breadth of (anticipated) damage. This could be expressed as a percentage of the total value (of the assets affected) with maximum potential (immediate and/or direct) damage equal to 100. Unfortunately, this does not take into account the ancillary damages which

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[2] Depending on the time perspective for analysis of cost associated with adaptation strategies, these may include both, highly focused-actions undertaken in the short and/or medium terms with an aim to mitigate and contain the scope/ duration of harm, injury and damage.

can expand over and beyond the initial range of harms and magnify the scope of initial injury via spreads to other related and/or unrelated areas.

On the other hand, damage occurring in a close or related environment (e.g. infrastructure) may also affect the functionality of rolling stock, leading to truck and/or train stoppages, and threatening the logistics missions.

The percent damage of an asset depends partly on the force of a strike and partly on the vulnerability of an asset. Yet the knowledge of vulnerabilities and/or vulnerability levels is generally poor (Aaheim et al., 2009). The vulnerability level of a given supply chain may for instance be affected by the technical quality of fleet equipment, how well it is maintained and operated, and how well the managing staff is qualified. In addition, the types and the level of risk affecting the mobile and immobile logistics assets may differ considerably. It is, however, beyond the scope of the EWENT study to delve into the details of these characteristics.

On the other hand, risks are commonly dealt with by insurance markets which apply a broader definition of risk than just the probabilities of hazards[3]. However, one problem affecting companies providing individual insurance against natural hazards is that the risks are unknown and the probabilities highly uncertain. Hence, the premiums may either be too high or too low as compared to the actual risk. The social efficiency of insurance markets is thereby undermined.

Further, managing risk by means of private insurance policies may also come into conflict with social norms given the different values assigned by the insurance industry to the value of statistical worker life in the different countries. The social postulate of the European Commission states that the life and health of all workers should be valued equally all over Europe.

Aaheim (2010) compiled data on estimated and observed health and security insurance expenditures in different industry sectors in Norway. Insurance expenditures related to fatality and injury accidents have been calculated assuming that the chances of their occurrence were equal within a given sector but differed with respect to magnitude and cost of damage/injury. The variation between sectors was huge. Bank, insurance, electricity and water supply sectors paid generously to avoid yet another accident. At the other end of the scale he found building, construction, transport, communication and manufacturing sectors that paid much less to avoid one more accident despite the fact

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[3] The author (Johanna Ludvigsen) surveyed several maritime insurance companies operating in Norway on the issue of how they accounted for risks of material damage/ life loss/ injury affecting shipping lines as a result of extreme weather on the seas. The answer was they did not. The standard solution was the so-called “casco-insurance” which covered risks arising from several hazard categories (including those of extreme weather). The bulk of damage/and injuries that over the last 10 years could be attributed to extreme weather accounted for 3 p.c. of all damage–causing incidents only registered until 2005. Beyond this point in time, the insurers did not collect any statistics on weather-related damage and/or fatalities.

that the levels of occupational hazards varied considerably between these industries, but were generally higher than those affecting workers in bank and insurance companies. Certainly, the wages paid by these sectors differed also, but wage variation was not nearly as large as the insurance expenditures.

In addition to a haphazard pattern in willingness to insure against health and security damage between the different industry sectors, violation of the basic social equality principle may also be used by the competitive insurance market to refuse an appropriate risk coverage. Aaheim (2010) maintains that this inadequacy in managing natural hazard risks is also pretty common across Europe and worldwide.

"Transformational" approach to risk management in the logistics industry

Taking stock of these findings, this note proposes a "transformational" approach to studying how the European logistics industry adapts to external risks arising from extreme weather conditions, and what containment strategies are used for dealing with extreme-weather hazards. This approach was developed by Christopher et al. (2010) and springs from a realisation that conventional logistics analysis does not grasp the high-level comprehensiveness of remote sourcing and value addition that occur through a plethora of logistics operations distributed across different geographical locations, all connected through interactions between the different layers of human actions, infrastructure, and technology applications. End-to-end supply chains are not smoothly linear. They usually start out from several geo-locations and move through several service provision stations, such as terminals and warehouses before entering transport vehicles, vessels and trains carrying cargo between factories, offloading docks, distribution centres and retailer outlets. All these components and their functions are integrated in hybrid business and operating models, evidencing that what works in one set of regions/countries and with one particular type of partners does not necessarily do so with others.

The transformational approach to logistics takes account of its hybrid composition and the high level of innate vulnerability that threatens the logistics reliability, plus the efforts spent to restore its functionality after/or even under the protracted impacts of external and internal contingencies.

4. Media mining and case descriptions

4.1 Database contents and events

In the EWENT project the media database was set up by collecting news from extreme weather phenomena dealing with transport systems of the European countries. The database now includes (10.9.2010) more than 190 different weather phenomena and their impacts on society since 1.1.2000 (see Appendix 1). Twenty-seven large autumn or winter storms that passed through the whole of Europe or at least a large part of it during the last 10 years were identified. These storms have had the most critical influences on the European transport network. They have caused impacts to road traffic, railways, aviation, inland shipping and ocean traffic.

In addition to these large storms there are some more regional weather phenomena that can affect various transportation systems. From the media database it appears that 79% of reported weather phenomena have had some effects on road transportation but only 36% of the phenomena have had an influence on railway transportation and only 13% on aviation (Figure 13). Phenomena that have affected aviation can be ranked as European-wide storms. These storms have also influenced inland shipping or ocean transport. Twenty-five percent of the phenomena have affected either ocean traffic or in inland shipping. Most of these extreme events have occurred in winter; only one fourth have occurred in the summer months. In the following, these events are discussed in relation to traffic mode and geographical area.

A review of media reports was carried out in English, German, Finnish, Swedish, French, Spanish, Greek and Hungarian. Approximately 190 extreme weather events were documented onto an MS-Excel worksheet. Most of the identified events were located in Spain (35) and the United Kingdom (31), while 19 events were found for Germany and 12 events for both Sweden and Finland. Other countries had fewer hits. In addition, 27 Europe-wide events were identified.

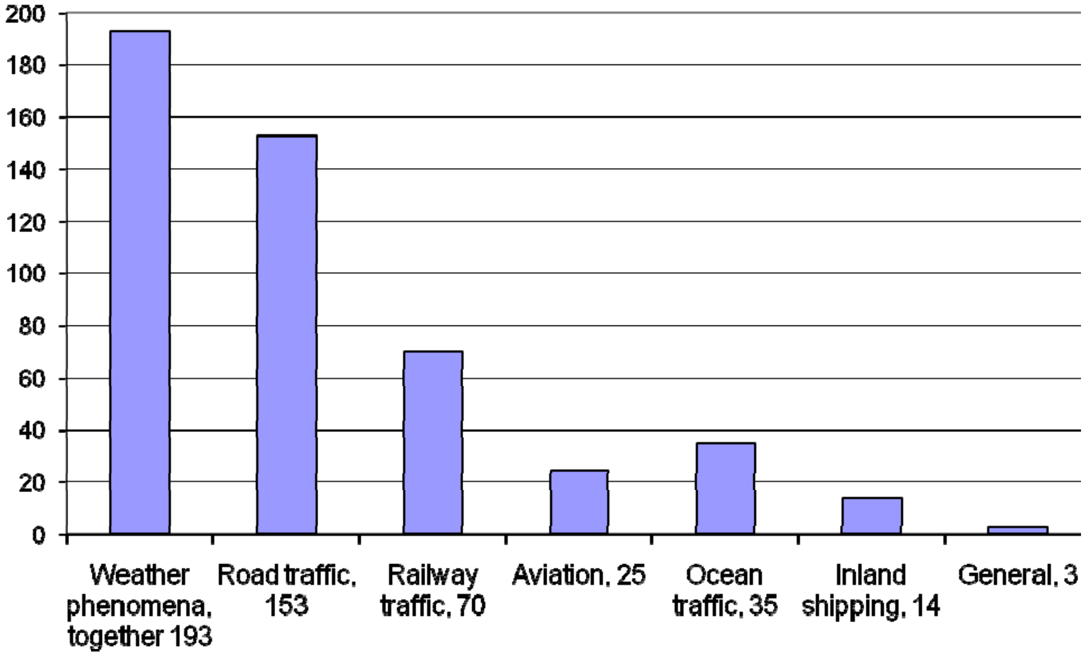

Figure 13. Amount of reported weather phenomena and their targets of impact.

More than half of the listed events were associated with heavy rain (79), heavy snow (59) or strong wind (81). Low temperature affected 15 of the listed events, and 11 events were found related to high temperatures. Hail was involved in 20 and Ice in 13 events. Fog was involved in eight and low visibility in eight traffic events. Landslides due to heavy rain had an impact on transport in 14 events.

About 40 of the listed events had been further clarified to describe flooding as a consequence of heavy rain or snow. Unfortunately, nowadays not all flooding events are due to exceptional rainfall but derive rather from excessive urbanisation and poorly planned run-off regimes.

As the work was done mainly by looking at news articles, the majority of reported events tend to be more recent. Depending on the provider, concrete event descriptions might only remain "in the news" for a couple of months (after which they may not allow open access to it), while others may continue to allow access to the complete range of their articles. Also, some news providers do not maintain a working archive. Obviously, this "availability aspect" has also had an influence on the events identified, with the authors not aiming to subscribe to any such news systems. Additionally, these archiving policies also affected the identified results – especially in regard to local consequences, only the local news provider reported extensively on the subject.

The consequences of extreme weather events have been seen to be both Europe-wide and very local. Harsh Europe-wide storms and outbreaks of wintry weather have very widespread effects, as indicated from the events of winter 2009–2010, where both local and nationwide traffic was paralysed by severe conditions. Obviously, also the level of habitation and access in any specific area will be related to the associated reported winter weather consequences.

Any “extreme” weather (no matter how mild in reality) will be exacerbated by lack of preparation and the availability of adequate measures; for instance, snow in southern countries may seem more disruptive because sufficient snow clearing equipment may not be available.

Heavy wind together with heavy rain was the most common phenomenon causing problems around Europe. Usually this phenomenon occurs in summer and can also include thunderstorms. Windstorms cause problems to the critical infrastructure through felled trees and floods, which in turn also affect traffic. Flooding was typically also associated with other infrastructural disruptions. Landslides can have severe consequences, but these are generally somewhat local in nature.

Heavy snow and freezing temperatures cause one the most widespread effects. Black ice is a relatively normal phenomenon at the end of winter in northern countries. No cases involving ice rain were identified. Winter weather consequences may also last for a longer period of time.

Hail is a good example of an extremely damaging weather phenomenon that may be very local. Even in this highly-reported socially-networked world, unless the event is extremely unusual, when the consequences remain local or minor the reports do not necessarily attract nationwide attention. Extremely dry weather was generally not reported, except when associated with forest fires. And heat waves were only seen to be reported, for instance, when water bottles were dispensed to car drivers.

According to the data of Swiss Re (2001–2010), it seems that Europe-wide storms often involve enormous insurance costs. For example, over the past 10 years five windstorms (Oratia, Jeanett, Gudrun/Erwin, Kyrill and Emma) have caused such huge costs that they have been listed among the 20 most costly insurance losses in the year they took place. Unexpectedly, one additional regional storm (Klaus) and two local weather phenomena (flash flood in Turkey and heavy rains in Switzerland) were also included in the same list.

Europe-wide storms cause the most serious and long-lasting damage to societies, like rebuilding costs of roads, railways, bridges and tunnels, lost income in aviation, and delays in logistics systems. These influences affect not only the areas where the storms hit, but also the surrounding economic areas. If large economic areas are hit by a storm, recovery will be slow; for example, some repairs may take a long time because of a lack of skilled workers. The overall economic consequence of traffic jams or paralysed train timetables is deemed difficult to judge, and no information was found in the database to clarify the issue.

Specific extreme weather consequences to traffic accidents are generally difficult to find. According to the statistical data, the majority of reported accidents occur in good driving conditions, not during storms. However, our database shows that the most harmful weather phenomena for human lives are winter conditions with heavy snow and ice or ocean storms. According to collected data 75% of all accidents occur on icy and snowy roads. Lethal accidents also occur on stormy seas. Seven of 29 reported accidents at sea resulted in loss of life, meaning that as many as 25% of ocean accidents in stormy seas are lethal.

According to our database there were no lethal accidents in railway traffic or aviation due to bad weather in the last 10 years; the storms incurred mainly delays and costs.

Extreme weather effects, conditions and consequences differ according to the location of the country, its geography, population distribution, infrastructure, and preparedness for different extreme weather conditions. In order to achieve greater insight into the phenomena and the associated relationships, a more substantial analysis of the different weather conditions and causes in different traffic areas would need to be performed.

4.1.1 Database events typified by region

Scandinavia

Almost all of the road and rail events identified in the Scandinavian media were related to winter conditions, and only a few of the 26 analysed events occurred in summer. The consequences on road transportation typically involved lower traffic speeds and interruptions due to traffic accidents. The two most typical harmful phenomena were heavy snow and rainfall, which slow down traffic or even require closing down some parts of the road network, causing delays and accidents. Also strong winds and low temperatures were identified as harmful phenomena. Strong winds fell trees onto the road network and cause delays and disruptions. Low temperatures cause slipperiness on the roads, which again encourages accidents, injuries and even deaths.

In Scandinavian rail transport strong winds have felled trees, broken contact wires and stopped or cancelled rail services in many locations. Once, railway traffic was disrupted for a month. Heavy snowfall and ice have caused serious delays and long lasting secondary effects to passenger rail services. Storm winds have caused severe disruptions to transport at sea.

Central Europe

Cold temperatures and heavy snowfall have been the main causes of stopped or cancelled rail services in Central Europe. Some effects from a hurricane have also been identified.

In Central Europe, heavy snowfalls seem to be the most harmful weather phenomenon causing traffic disruptions, road closures and serious injuries (and deaths). Also minor snowfalls, particularly when complemented by strong wind and temperatures below 0^{o}C, cause slipperiness and accident risks. In addition, heavy rains cause flooding, which again affect the road network and infrastructure conditions.

Inland waterway transport has to deal with weather events affecting navigation conditions and the infrastructure. Most significant extreme weather events result from high precipitation, droughts and temperatures below 0°C. Heavy rainfall, in particular in association with snow melt, often leads to floods, resulting in suspension of navigation and causing damage to the inland waterway infrastructure as well as to the property and health of people living in areas exposed to flooding. Long periods of drought may lead to reduced discharge and low water levels, limiting the cargo-carrying capacity of vessels and increasing their sailing times, in particular, when sailing downstream. Also, temperatures below 0°C over a longer period may cause ice to appear on waterways, leading to suspension of navigation and possible damage of infrastructure, e.g. buoys.

Mediterranean

In the Mediterranean region, heavy winter rainfalls have caused flooding and mudslides, which have disrupted road transport seriously, e.g. by closing down road sections for up to a month; rail transport has also been slightly disrupted but not as seriously as road transport. High temperatures cause a risk of forest fires and bushfires, which harm and hinder the traffic on roads and railways.

In the Mediterranean Maritime area, roughly once every 2 years weather conditions evolve that cause disruptions to sea traffic. The most common phenomenon is strong wind, which causes delays, engine failures, grounding and even shipwrecks. The other delay-causing phenomenon is fog, which can close ports. During the last 10 years there have been three fatal accidents and one major environmental accident (oil spill).

Other regions

The majority of other identified events occurred in the autumn and winter in the United Kingdom. A wide range of different weather phenomena were identified: heavy rain and wind, landslides due to heavy rain, icy roads and heavy snow, fog, hail and ice, etc. The highest number of identified events related to heavy rain (sometimes complemented with low temperatures or snowfall). The events caused flooding on the roads, landslides, and consequent closing of roads, traffic jams and accidents. Also heavy snowfalls and low temperatures caused accidents and road closures. In addition, hail and fog caused traffic problems.

Low temperatures, ice and heavy snowfalls have caused cancellations of rail services in the UK. In one incident, passengers were trapped in the Eurotunnel. Also heavy rain and consequent flooding has disrupted rail services.

In the Alpine region, heavy rain has caused delays to cargo transport on roads. However, within this region the level of preparedness is high, i.e. people and authorities are used to dealing with severe conditions. Consequently, precautions are often taken beforehand.

Table 5 includes a summary of reported extreme weather phenomena in different regions.

Table 5. The most harmful weather phenomena identified by mode and region, based on a media study.

ROAD TRANSPORT				
Phenomena	*Scandinavia*	*Central Europe*	*Mediterranean*	*Other (U.K.)*
Heavy Snow	√	√	√	√
Heavy Rain	√	√	√	√
Strong wind	√	√		
Low temperature	√	√		√
RAIL TRANSPORT				
Phenomena	*Scandinavia*	*Central Europe*	*Mediterranean*	*Other (U.K.)*
Heavy Snow	√	√		√
Heavy Rain		√	√	√
Strong wind	√			
Low temperature	√	√		√
WATERBORNE TRANSPORT				
Phenomena	*Scandinavia*	*Central Europe*	*Mediterranean*	*Other*
Heavy Snow				√
Heavy Rain		√	√	√
Strong wind	√	√	√	√
Low temperature	√	√		
Drought		√		
AIR TRANSPORT				
Phenomena	*Scandinavia*	*Central Europe*	*Mediterranean*	*Other*
Strong wind	√	√	√	√
Thunderstorms and lightning	√	√	√	√
Low visibility, associated with cloud, mist, fog, snow	√	√	√	√
In-flight icing, ground icing	√	√		
Sandstorms			√	

4.2 Case descriptions and events

In the EWENT document authored by ESSL, events in Europe are categorised into five climatic zones: Scandinavian, Temperate, Alpine, Mediterranean and Maritime (N/S) (see chapter 2). The following events are described along the same lines.

4.2.1 Scandinavian climatic zone events

Almost all the identified events of the Scandinavian climatic zones were related to winter conditions, and only three events out of 27 occurred in summer. Based on our search, examples of extreme weather phenomena in the Nordic zone included strong winds, heavy rain or snow and some low temperatures. The consequences on road transportation typically involved lower traffic speeds and interruptions due to traffic accidents. Strong wind also affected sea transport.

Storm Janika (Finland), 15.–16.11.2001

The storm resulted in extensive material damage and major disruptions to traffic flow. Fallen trees and broken contact wires stopped rail services in many places. Fallen trees also blocked roads, caused accidents and affected road traffic.

Winter storm Rafael (Finland), 22.–23.12.2004

Rafael was the strongest storm in Finland in 2004; it felled trees, unroofed buildings and disrupted electricity over wide areas. Due to slippery roads, snow and strong winds, road traffic was also badly affected. The worst traffic accident involved a Helsinki-Turku coach, which swerved off the road into an adjoining river. One fatality was reported and 20 injured. All other night service coaches between Helsinki and Turku were cancelled.

Windstorm Gudrun (Sweden), 7.–9.1.2005

Windstorm Gudrun (also known as the Erwin storm) battered Northern Europe from Ireland to Russia, killing 17 people mostly in Sweden and Denmark. The storm severely disrupted all modes of transportation – at sea, in the air and on land. Many roads where closed due to trees felled by the storm. However, the road authorities were prepared and many of the major and mid-sized roads re-opened within a couple of days. The railways were affected more than the roads, and rail traffic was disrupted for about a month. The storm caused widespread property damage, and floods and powerful winds cut power to around 500 000 homes. In Sweden, forest-related damage was the worst in recorded recent history and resulted in disruption to power supplies, phone lines and railway traffic.

Heavy snow (Finland) – 1.11.2006

The first really wintry and snowy weather in the autumn 2006 resulted in long-lasting heavy snow that badly affected traffic conditions in Southern and Central Finland over a period of 3 days. Transportation was severely affected with trucks becoming trapped and all traffic moving extremely slowly on hilly roads. Dozens of trucks became stuck on the main road E4 in the Lusi area. Frontier traffic between Finland and Russia was badly disrupted because of trucks sliding off the road, and some frontier stations were even closed. Many train services were also delayed, with several long-distance trains being held up for hours between stations because of the heavy snow or fallen trees.

Case VR (Finnish railway group) – winter 2009–2010

Harsh winter conditions were blamed for numerous disruptions to railway transportation all over Europe. The exceptionally hard winter of 2009–2010, with a lot of snow and low temperatures, seems to have affected especially train traffic in the Nordic countries, which have therefore had to implement special timetables for a longer period. For instance, in Finland many long-distance trains and Helsinki metropolitan area rail traffic was constantly delayed due to heavy snow and windy conditions. During February, much of the local traffic and many long-distance trains were cancelled. This was a very unusual situation in Finland. Very harsh weather conditions were blamed, of which the following were key elements: heavy snow, low temperatures and windy weather. At the height of disruptions, general discussions also arose on whether the Finnish army should participate to help remove snow from the railway lines. In Sweden, the army was seconded to clear the Swedish rail system during February.

4.2.2 Temperate climatic zone events

Almost all events identified for France, Germany and the Netherlands occurred during the time period from November to March – only one listed event transpired in June and it only had minor consequences to traffic. Significant impacts to road traffic were observed due to exceptionally harsh conditions during the winter of 2009–2010. Many areas reported that salt/grit supplies had run out, even while it continued to snow heavily. The events were mainly related to strong winds, heavy snow, heavy rain, black ice, and flooding. Because of very high traffic densities and the occasional unpreparedness of drivers for sudden extreme winter conditions, many traffic jams and general chaotic conditions were reported. Lorry transportation was at one time forbidden in parts of France.

Heavy rain (EUROPE) – August 2002

A “100-year flood”caused by severe rainstorms caused havoc across Europe – mainly in the Czech Republic, Slovakia, Italy, Spain, Germany, Romania, Bulgaria, Croatia, Hungary, and Ukraine. Several rivers in the region, including the Vltava, Elbe and Danube, reached record highs. Although all of Europe was affected to some degree from the record rains that fell, some cities were spared the severe flooding that hit Dresden and Prague. More than 70 people are known to have died. In the Czech Republic alone, at least eight people died, road and rail lines were cut and towns and cities swamped. Prague’s underground platforms lay beneath 120 feet of water, which also submerged two trains still on the tracks at the station.

Heavy snow (Germany) – January 2010

Heavy snowfall caused chaos in Germany. Cars were stuck in the snow and police warned the public not to drive. Many streets were not navigable, and instances of car drivers waiting for hours for assistance were reported. Train traffic was also badly affected.

Hurricane-force storm Xynthia (Western Europe) – February 2010

The hurricane-force winds and rain of Atlantic storm Xynthia whipped through Western Europe at the end of February after lashing the coasts of France and Spain. Dozens of people were killed and more than a million homes left without power. More than 12 hours after the storm passed through France, roads were still flooded and streets filled with debris. Sea walls protecting coastal towns were destroyed, allowing water to rise quickly. Flooded railway tracks led to railway delays in France. Because of the severity of consequences and fatalities, consequences to traffic and transportation were not specifically highlighted in the reported news.

4.2.3 Alpine climatic zones events

Quite unexpectedly, only two events related to the Alpine climatic zone were found. It had been assumed that difficult weather phenomena would more easily disrupt transportation in the mountainous areas around the Alps (including tunnels and bridges). The level of preparedness was considered to be a significant feature; as heavy snow or rain falls can be expected in the Alps, people and authorities are used to dealing with severe weather conditions, and precautions are taken in advance. While the weather may cause disturbances to traffic, such events may be considered "normal" for those locations and conditions. Flooding, landslides and avalanches are possible events associated with heavy rain or snow. The risk of heat waves is currently a hotly debated phenomenon.

Both of the identified Swiss events are from August and involve heavy rain. The first report described how cargo train traffic had again to normalise after a heavy storm, while the other centred on flooding rivers, which resulted in train delays and difficulties on many roads.

4.2.4 Mediterranean climatic zone events

In the Mediterranean climatic zone, there was perceived to be more variation in which season the notable weather events occurred. Nevertheless, most of the identified events took place in late summer, in the autumn, or during the winter. Even though the Mediterranean climatic zone is geographically very diverse, most of the identified events were located in Spain.

When compared to the previous three climatic zones, there was also more variation in what kinds of weather events affected transportation. Heavy snow and heavy rain events were also noted, but in addition, landslides were commonly associated with, for instance, heavy rain. High temperatures were also associated with transportation delays mostly due to forest and bush fires.

Forest fires disrupted a fast train line (Spain) – July 2009

Forest fires in Spain forced an interruption of service of the bullet train between Madrid and Barcelona, affecting more than 6 000 passengers. However, it was noted that Spain is plagued by forest and brush fires every summer, when extremely dry weather sets in along with high temperatures.

Landslide (Italy) – October 2009

Apparently over 200 cm of water fell within 1 hour, creating devastating flash floods and mudslides. Twenty-four people were killed and the Italian state declared a state of emergency. Roads and railways were cut and many of the stricken areas were accessible only on foot after mud clogged the city’s streets.

4.2.5 Maritime (N/S) climatic zone events

Most of the identified Maritime climatic zone events occurred in autumn and winter, with the majority taking place in the United Kingdom. A wide range of different weather phenomena were identified: heavy rain and wind, landslides due to heavy rain, icy roads and heavy snow, fog, hail and ice, etc.

Heavy snow and icy weather (UK) – winter 2009

Delays to train services. Local authorities in some areas gave up trying to clear minor roads after running out of gritting salt and concentrated only on main routes. Some roads were totally closed off in badly iced areas.

Landslide after heavy rain (UK) – winter 2009

Train services were in a state of chaos as flooding prevented railway traffic in some affected areas. Fire and rescue crews were called out to help motorists left stranded after a river burst its banks.

4.2.6 Mediterranean climatic zone events – maritime

Strong winds, high waves, sandstorms and fog are the weather phenomena identified in 3.2.6 that affect short-sea shipping in the Mediterranean.

Storm, snowstorm, sandstorm – winter 2004

In storm winds of up to 8–9 BF and waves up to 6–7 m the Kephi freighter sunk with 15 fatalities 120nmi west of Crete in the SOUTHWEST KRITIKO area (No. 30, Appendix C). The Suez Canal and several ports were closed during the storm.

Storm – winter 2005

The cruise ship Voyager was caught in a storm near Palma Mallorca, in the CABRERA area (No. 14, Appendix C). Winds were up to 10–11 BF and waves up to 10–14 m. The ship, which carried 732 passengers, suffered engine problems and issued SOS calls.

Sandstorm, reduced visibility – winter 2006

In winds of 6 BF, the Okal King Dor cargo ship drifted inside the Suez Canal and blocked it, causing delays and costs to maritime transport.

Storm – autumn 2008

In winds of 9–10 BF and 10 m waves, the MV Fedra cargo ship crashed near Gibraltar in the ALBORAN area (No. 0, Appendix C). The vessel broke in half and 300 tons of fuel spilled into the sea.

Heavy fog – autumn 2009

Heavy fog closed the Bosporus strait between MARMARA and the WEST BLACK SEA (Nos. 50 & 52, Appendix C). The closure caused delays to oil tankers crossing the strait.

Storm – winter 2009

In storm winds of 8 BF and waves of 6–7 m, Danny F II capsized near Lebanon in the CRUSADE area (No. 34, Appendix C). On board were 83 people, of whom only 25 were rescued.

Storm – spring 2010

In a storm of 9–10 BF winds and 8–9 m waves, the Louis Majesty cruise ship was hit by a wave near Marseilles in the PROVENCE area (No. 11, Appendix C), with two fatalities.

5. Critical parameters of weather and indicators of transport system

5.1 Transport system

Basically, the ultimate purpose of the transport system is to serve the needs and expectations of the end users, who in turn shape the system by their own behaviour and actions. The transport system is thus both socially constructed and society shaping. The state of the transport system is a result of the measures and actions carried out by the producers, operators and users of the system (Figure 14). Producers and operators are organisations or companies, which can be categorised according to their main duties, such as: (1) policy formulation, (2) infrastructure construction and maintenance including terminals, (3) production and operation of services for the transport system, and (4) production of transport-related services (e.g. vehicle manufacturing and fuels). Some of these categories (especially (2) and (4)) have traditionally been divided further into transport mode specific segments. Producers gather information on the state of the transport system and also receive feedback from customers, i.e. the users of the transport system. They make plans on the grounds of expert knowledge (design principles), and decisions based on generic or special decision-making principles. Within the process, information about the system gathered by the producers is, or at least should be, transformed into policy measures, aiming to lead the transport system into the desired future.

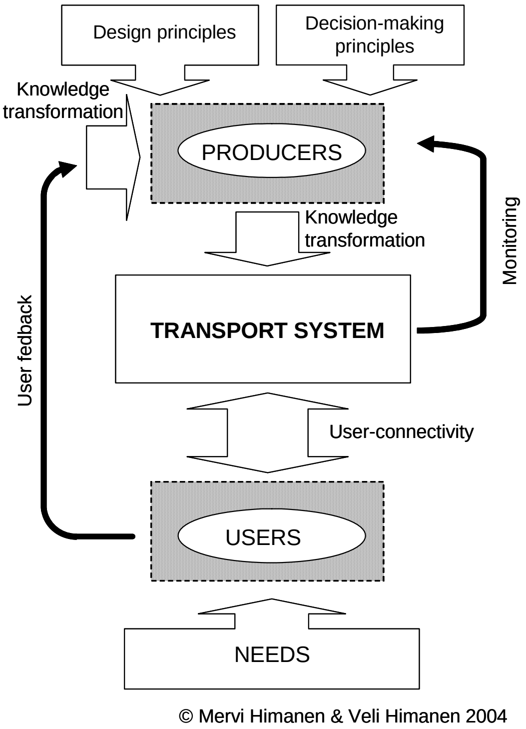

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Figure 14. Producers, users and interactions within the transport system.

Individual people, actually the whole population, are the users of the passenger transport system. Users may be further divided into pedestrians, cyclists, car drivers and bus, train, boat and aircraft passengers. In addition, leisure boating and aviation may be considered as separate end user groups.

In freight transport, companies and organisations in the field of industry, transport and commerce are the users of the transport system. They operate either with their own vehicle fleet or outsource their transportation to a special transport company. Also individual people, e.g. in the fields of agriculture and forestry, may be considered as users of the freight transport system.

Figure 15 presents a slightly different view on the transport system. It looks at the transport system through transport mode specific segments of infrastructure networks, transport services and the vehicle fleet. Policies and regulations, terminals and management of the mode related segments are considered here as shared parts of the transport system.

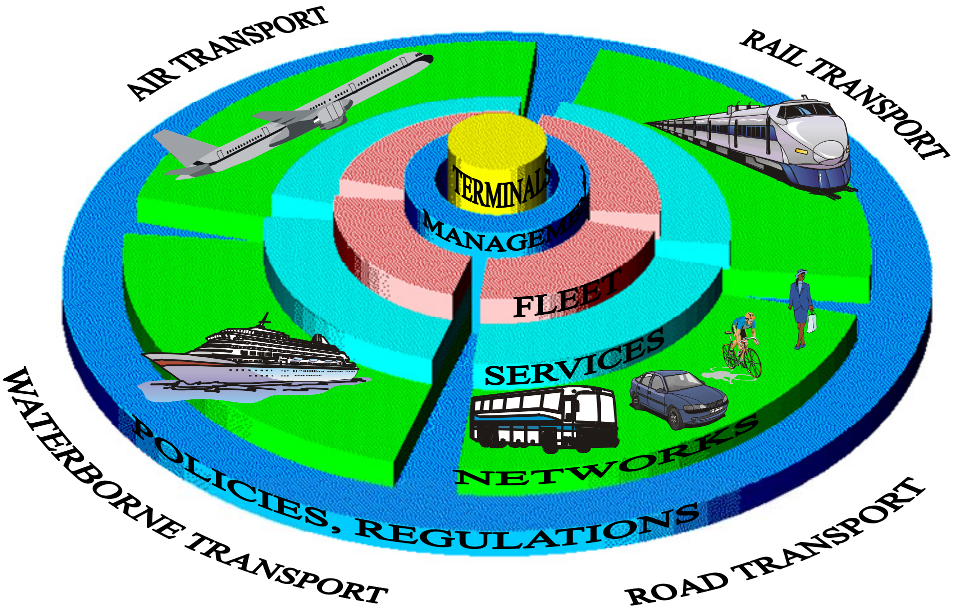

Figure 15. One view of the transport system.

In the EWENT project we look at the transport system mainly through the latter definition, complemented with the end user perspective (for both passenger and freight transport), identified in the former definition.

5.2 Transport system performance indicators

5.2.1 Definitions

Indicators are things that we measure in order to evaluate progress towards goals and objectives. Indicators should be carefully selected to provide useful information (USEPA, 2008). In most situations, no single indicator is adequate, so a set should be selected. An indicator should reflect various goals and objectives.

Indicators can reflect various levels of analysis, as illustrated in Table 6. For example, indicators may reflect the decision-making process (the quality of planning), responses (travel patterns), physical impacts (emission and accident rates), effects this has on people and the environment (injuries and deaths, and ecological damages), and their economic impacts (costs to society due to crashes and environmental degradation). An index can include indicators that reflect various levels of analysis, but it is important to take their relationships into account in evaluation to avoid double counting. For example, reductions in vehicle-mile emission rates can reduce ambient pollutants and human health damages; it may be useful to track each of these factors, but it would be wrong to add them up as if they reflect different types of impacts.

Table 6. Levels of analysis (adopted from Litman, 2009) This table shows how indicators can measure various levels of impacts, from the planning process to travel behaviour, impacts on people and the environment, and economic effects.

Level	**Examples**
External Trends ▼	Changes in population, income, economic activity, political pressures, etc.
Decision-Making ▼	Planning process, pricing policies, stakeholder involvement, etc.
Options and Incentives ▼	Facility design and operations, transport services, prices, user information, etc.
Response (Physical Changes) ▼	Changes in mobility, mode choice, pollution emissions, crashes, land development patterns, etc.
Cumulative Impacts ▼	Changes in ambient pollution, traffic risk levels, overall accessibility, transportation costs, etc.
Human and Environmental Effects ▼	Changes in pollution exposure, health, traffic injuries and fatalities, ecological productivity, etc.
Economic Impacts ▼	Property damages, medical expenses, productivity losses, mitigation and compensation costs.
Performance Evaluation	Ability to achieve specified targets.

Performance indicators can be categorized in the following way:

- *Process* – the types of policies and planning activities, such as whether the organization has a process for collecting and publishing performance data, and public involvement.
- *Inputs* – the resources that are invested in particular activities, such as the level of funding spent on various activities or modes.
- *Outputs* – direct results, such as the miles of sidewalks, paths and roads, and the amount of public transit service provided.
- *Outcomes* – ultimate results, such as the number of miles travelled and mode split, average travel speeds, congestion and crowding, number of accidents and casualties, energy consumption, pollution emissions, and user satisfaction.

Data serving performance indicators can be either quantitative or qualitative. Quantitative data refers to numerically measured information. Qualitative data refers to other types of information. In the EWENT project, however, quantitative data is preferable.

5.2.2 Transport system performance indicators in the context of extreme weather

The EWENT project aims to estimate the consequences of extreme weather events to the transport system, estimate their risks and costs and, further, identify possible mitigation strategies. Transport system performance indicators are needed in EWENT in order to build descriptive and/or quantitative links between extreme weather parameters (events) and the parts of the transport system the consequences of extreme weather are predicted to affect.

The EWENT project Description of Work proposed to view the transport system from three perspectives:

- *Infrastructure*; these are direct material damages or deterioration of physical infrastructures
- *Operations*; these are harmful impacts on traffic safety and transport reliability (both freight and passenger)
- *Indirect impacts to third parties*, e.g. supply chain customers and industrial actors.

These perspectives may also adopt different time horizons, i.e. some risks are dealt with on a day-to-day basis (how to prepare for and eliminate sudden extreme weather with short-term measures) and some are strategic in nature (how to prepare in the long term to face extreme phenomena, by e.g. changing the standards of transport infrastructure).

Many different kinds of categorizations for transport system performance indicators have been developed, on both international and national levels. Examples of those are the European Framework Programme projects MAESTRO (Monitoring, Assessment and Evaluation of Transport Policy Options in Europe), SUMMA (Sustainable Mobility, policy Measures and Assessment) and HEATCO (Developing Harmonised European Approaches for Transport COsting and project assessment), the national project TILA (A Finnish view on end user oriented transport system performance indicators (2010). Also the European Commission guide to cost-benefit analysis (European Commission 2008) provides one perspective.

Based on the previous research and consortium expertise, we propose the following preliminary transport system performance indicator categorization, which may and will be elaborated further in the forthcoming phases of the project, especially in Work Package 3. The categories are presented in Table 7.

Table 7. Preliminary EWENT transport system performance categories describing the parts of the transport system the consequences of extreme weather are likely to affect.

Performance category	**Impact/ Indicator area**
Infrastructures	Physical infrastructures (e.g. material damages to road, rail, ports, airports, terminals [km, km^2])
	Use of existing networks (e.g. passenger-km and ton-km by transport mode)
	Intermodality (interchange nodes, accessibility to ports and airports, other terminals)
	Interoperability
	Management of infrastructures
Service level, passenger transport	Accessibility (e.g. accessibility of basic daily services, terminals, services)
	Quality of supply (e.g. transport services: routes, timetables, fleet, frequency)
	Functionality (e.g. fluency (journey times, waiting times), predictability, comfort, security of a journey)
	Information (e.g. availability, quality)
	Tariffs (e.g. out of pocket costs)
Service level, freight transport	Accessibility (e.g. available links and services)
	Quality of logistic services
	Functionality (e.g. accuracy, predictability, delays, inferences)
	Information (e.g. on the different phases of the logistic processes, on delays, interferences)
	Transport and logistic costs
Externalities etc.	Accidents in passenger transport, dead and injured persons by mode
	Accidents in freight transport, dead and injured persons by mode
	Air pollution + CO_2
	Noise
	Driving / operating speeds
	Quality of rescue services
Indirect impacts	Regional development
	Employment
	Economic development
	Legal impacts
	Health impacts

5.3 Threshold values for critical weather parameters and their impacts and consequences

5.3.1 Threshold values for winter conditions

Based on the literature and impact reviews as well as reviews of hazardous cases, impact thresholds for snowfall, wind gusts, low temperature and blizzards with explanations have been defined (Table 8). Three threshold values were chosen for each weather parameter. The values can occur in most parts of Europe in the present climate. The warning criteria of European weather services (basically those involved in the Meteoalarm warning service) were looked through and utilized in the decision making. Also the information of impacts (impact review, literature etc.) was used. The time frame in precipitation (24 h) corresponds to the output from the climate models.

Table 8. Threshold values for winter conditions.

Low temperature – daily mean temperature		
Threshold	**Impacts**	**Consequences**
≤ 0°C	This is an important threshold related to slipperiness (ice formation, form of precipitation: rain/sleet/snowfall). The temperature itself is rather a modifier of hazardous conditions for transportation than a main cause. Low temperature combined with precipitation and wind can have a disruptive effect on traffic. Occurrence of freezing drizzle, increased frequencies of freeze-thaw cycles.	Increased accident risk in road traffic. The occurrence of freezing drizzle might be hazardous for aviation and road traffic. Premature deterioration of road and runway pavements.
≤ -7°C	The effect of salting for ice removal decreases in low temperatures. So, even relatively small amounts of snowfall can cause slippery conditions on highways when packed on the road surface by traffic. Rail points may get stuck by drifting snow in low temperatures (observed in Finland and Canada). Ice formation on rivers may start if there are many cold days in a row. Some vehicles might have fuel problems (“summer diesel sort”).	Increased accident risk, delays and cancellations in road and rail traffic (e.g. Eurostar trains during winter 2009/10). Inland waterway transport might be disrupted.
≤ -20°C	Some vehicles might have fuel problems (Oslo, winter 2009/10). Rivers get ice-covered if there is a long-lasting cold period. Dangerous wind chill conditions occur when moderate winds prevail.	Public transport may encounter breaks due to fuel problems. (Oslo, winter 2009/10), riverboat traffic may stop. Limitations to transport personnel working outdoors.

Snowfall (1 mm precipitation equals approximately 1 cm of snow)		
Threshold	**Impacts**	**Consequences**
≥ 1 cm/24 h	This is the practical lower limit of snowfall occurrence that is reasonable to use in climatic calculations. In some situations can cause slipperiness, for example combined with very cold conditions (below -10°C, increased accident rate observed in Finland). In the Mediterranean countries, where it seldom snows, it can also cause trouble. The shallow snow layer might melt and then form an icy layer (if the road is not salted), for example after sunset.	Slightly increased accident rate.
≥ 10 cm/24 h	Causes slipperiness on roads when combined with low temperature and wind; rail points may get stuck.	Increased accident rate in road traffic (double accident rate compared to the mean, observed in Finland); delays and cancellations in road traffic (e.g. serious problems in public transport in Central/Southern Europe, such as the "London buses" situation), in rail and air traffic.
≥ 20 cm/24 h	Slippery roads and runways, accumulated snow banks. Snow accumulation of 20 cm/24 h or more does not occur very often in lowland districts. For example in Helsinki city in Finland, winter 2009/10 was quite tough, but the biggest 24 h precipitation during December–February was only 10.1 mm on 1 February, corresponding to a snow depth increase of 10 cm. During the last 10 years in Helsinki city there were only four cases when the precipitation amount of the snowfall event exceeded 20 mm/24 h. One of the biggest events was recorded on 21/22 December 2003. Then the 24 h precipitation was 24.9 mm and the snow depth increased by 27 cm. At least double the car accident rate occurred, with bad traffic jams just before Christmas.	Disturbed traffic, high accident rate, temporary closed roads (e.g. trucks stuck in snow banks, Sweden, highway E4, on 17 Dec. 2009), airfields temporarily closed (as during winter 2009/10 in many cities in Central and Southern Europe), delays and cancellations in rail traffic.

Wind gusts		
Threshold	**Impacts**	**Consequences**
≥ 17 m/s	Trees can fall over roads and cars and on railway electricity lines.	Suspension of small boat operations, local/occasional problems in road and rail traffic (big problems if combined with snowfall).
≥ 25 m/s	A lot of fallen trees. Prolonged electricity cuts, reduced visibility due to blowing snow, dust, debris.	Prolonged electricity cuts, delays and cancellations in air, rail and road traffic. Ferry traffic severely disrupted with only larger vessels allowed out.
≥ 32 m/s	Fallen trees over roads and rail lines, widespread and prolonged power failures possible. Reduced visibility, high waves at sea.	Ferries stay in port, airfields are closed. Major material damage. (If a blizzard, “everything stops”).
Blizzard		
Threshold	**Impacts**	**Consequences**
Snowfall ≥ 10 cm/24 h, wind gust ≥ 17 m/s and daily mean temperature ≤ 0^{o}C	Fallen trees, snow banks, slippery roads and runways, poor visibility, rail points may get stuck.	Increased rate of injuries and accidents in road traffic (2–4 times more accidents compared to the mean), delays, and cancellations/stops in all transportation modes.

5.3.2 Mode-specific threshold values

The following tables present several other threshold values for different transport modes based on the EWENT literature review.

5.3.2.1 Thresholds for road and rail transport

Three threshold values were chosen for each weather parameter. The aim is that the values can occur in most parts of Europe in the present climate. The warning criteria of European weather services (basically those involved in the Meteoalarm warning service) were looked through and utilized in the decision making. Information on impacts (impact review, literature etc.) was also used. The time frame of precipitation (24 h) corresponds to the output from the climate models.

Table 9. Threshold values for road and rail transport.

High temperature – daily maximum temperature		
Threshold	**Impacts**	**Consequences**
≥ 25°C	Fatigue among bus-drivers and truck-drivers.	Possible increased crash rate in road transportation.
≥ 32°C	Damage to pavement, e.g. softening, traffic-related rutting, migration of liquid asphalt, roadway buckling. Restrictions in road maintenance and construction.	Increased accident rate, delays, diversion.
≥ 43°C	Rail equipment failure, rail track buckling, heat exhaustion.	Increased accident rate, delays, diversion.
Heavy precipitation		
Threshold	**Impacts**	**Consequences**
≥ 50 mm/24 h	Flooded roads, reduced pavement friction.	Damage to secondary (sand-covered) roads, increased collision risk on roads.
≥ 100 mm/24 h	The sewer system fills up; water rises to street level from drains. Rainwater fills underpasses and lower lying streets. Drain well covers may become detached and cause danger to street traffic. Reduced visibility, flooded underpasses.	Increased rate of road accidents, delays, damaged roads.
≥ 150 mm/24 h	Road structures may collapse and gravel roads are badly damaged. Bridges may be flooded. The metro system might be flooded, damaging track switch motors, the signalling system, power distribution system (e.g. Boston, Seoul). If a car is driven into deep enough water, the motor stops and may be flooded. Rainfall may induce landslides causing wash-out of roads or rail tracks. Roads and rails might be covered by water or by transported debris, mud (Southern France June 2010, 180 mm/12 h, train stuck on track due to water and debris).	Disrupted traffic, increased rate of road accidents, delays in road, rail and air traffic, damaged or closed roads and rail tracks, damaged metro systems.

5.3.2.2 Thresholds for aviation

Table 10. Threshold values for aviation.

Heavy precipitation		
Threshold	**Impacts**	**Consequences**
30 mm/ 1 h	Route blocked, runways closed; loss of situational awareness	Delays, diversion, accident, incident,
60 mm/ 6 h	APT limited infrastructure	Delays, diversion
90 mm/12 h	APT limited infrastructure, total APT closed	Diversion
150 mm/24 h	APT limited infrastructure, total APT closed	Diversion
Hail		
Threshold	**Impacts**	**Consequences**
Diameter: 2.0–4.0 cm	Route blocked, airport closed; Damage to a/c & APT, loss of situational awareness	Delays, diversion, accident, incident, ground damage
Diameter: 4.0–6.0 cm	Route blocked, airport closed; Damage to a/c & APT, loss of situational awareness	Delays, diversion, accident, incident, ground damage
Tornado		
Threshold	**Impacts**	**Consequences**
F1 (33 m/s)	Route blocked, airport closed, damage to a/c & APT	Delays, diversion, damage to a/c on ground, maintenance
F2 (50 m/s)	Route blocked, airport closed, severe damage to a/c & APT	Delays, diversion, damage to a/c on ground, maintenance
Lightning		
Threshold	**Impacts**	**Consequences**
APT: CG in 5 km radius	Route blocked, airport ground operation interrupted, damage to a/c & APT, loss of situation awareness	Delays, diversion, accident, incident, maintenance, ground damage
Sand storm		
Threshold	**Impacts**	**Consequences**
0.2–2 mg/m^3, Red VFR > 2 mg/m^3, Black	Airspace closed, erosion of hull and windows	Diversion, cancellation, reduced manoeuvrability
Wind		
Threshold	**Impacts**	**Consequences**
Head wind Vhead<Vmin	Reduced ground speed	Reduced landing rate, delay
Tail wind 10 kt for 4 km RWY	Reduced lift / Moderate take-off, landing	Reduced runway capacity, ground strike, too fast
Cross wind/gust a/c dependent	Stabilization of a/c / Moderate in landing	Reduced runway capacity, go-around, ground strike

Low visibility

Threshold	**Impacts** *(airport and aircraft specific)*	**Consequences**
CAT I : decision height (DH) >= 60 m, runway visual range (RVR) >= 550 m	Separation between aircraft increased	Delay
CAT II : 30 <= DH <= 60 m; RVR >= 300 m	Separation further increased	Delay, missed connections controlled flight into terrain
CAT III a : 15 <= DH <= 30 m; RVR >= 200 m	Separation further increased	delay controlled flight into terrain
CAT III b : DH < 15 m; 75 <= RVR < 200 m	Separation further increased	severe delay controlled flight into terrain
CAT III c : DH = 0 m; RVR = 0 m	Airport closed	very severe delay incoming flights diverted to other airports; outgoing flights cancelled; controlled flight into terrain

Turbulence

Qualitative categories	**Impacts**	**Consequences**
Light	Slight, erratic changes in altitude and/or attitude or slight, rapid and somewhat rhythmic bumpiness without noticeable changes in altitude or attitude	Passenger discomfort
Moderate	Similar to light turbulence, but greater intensity; changes in altitude/attitude occur; variations in indicated air speed	Passenger discomfort; flight altitude change if prolonged; injuries to crew
Severe	Large, abrupt changes in altitude/attitude; large variation in indicated airspeed; aircraft may be temporarily out of control	Incident, injuries to crew and passengers
Extreme	Aircraft is violently tossed about and is impossible to control	Structural damage, accident

In-flight icing/snow

Threshold	**Impacts**	**Consequences**
-40°C< T<6°C 20 µm<D<500 µm	Icing of a/c, loss of control	Diversion, delay, controlled flight into terrain

Volcanic ash

Threshold	**Impacts**	**Consequences**
0.2–2 mg/m^3, Red VFR > 2 mg/m^3, Black	Airspace closed, erosion of engines	Diversion, cancellation, loss of thrust

5.3.2.3 Thresholds for marine / short sea transport

Table 11. Threshold values for marine / short sea shipping.

Wind mean speed	
Threshold	**Impacts, arguments for using the threshold**
15.5–18.9 m/s 30–37 KT Near gale – gale winds 7–8 Beaufort	May encounter problems entering/leaving/anchoring at a certain port depending on the direction of the wind. At open sea caution is advised for ferries/smaller vessels.
19–22.6 m/s 38–44 KT Gale – severe gale winds 8–9 Beaufort	Extra measures should be taken on entering/leaving/anchoring at a port. Ferries and smaller vessels under these circumstances usually stay in port and only larger ships take to the open sea.
22.7–26.4 m/s 45–52 KT Severe gale – storm winds 9–10 Beaufort	Vessels should seek shelter and safe anchorage at ports. Ferries and smaller vessels stay in port and extra measures are required for larger ships, which may include rerouting.
Visibility – Fog	
Threshold	**Impacts, arguments for using the threshold**
< 1000 m > 6 h	Caution should be taken for any vessel cruising. Speed should be reduced.
500 < <1000 m > 6 h	The vessel should be in an alert state and speed should be further reduced.
< 500	The vessel should send sound signals and reduce speed to a minimum.

5.3.2.4 Thresholds for inland waterway transport

For inland waterway transport it is not possible to give a single weather criterion e.g. amount of precipitation during a time period for evaluation of whether a critical weather situation is given affecting the inland waterway transport system adversely. The reason may be traced to the complexity of the transport system and the variety of factors determining whether a weather constellation is becoming critical or not. E.g. discharge, water levels and flow velocities determining the navigation conditions of inland waterways are affected by the intensity and duration of precipitation. However, a common critical value for the duration and intensity of precipitation, leading e.g. to floods, cannot be given as this value will be different for different waterways and different locations of the same waterway. Small waterways are more vulnerable to the intensity and duration of precipitation, while large waterways can withstand large amounts of precipitation without flood occurrence. Further, the topology of the river catchment, e.g. presence of mountains and the size and amount of tributaries, plays a role in the development of hydrological events as well as the seasons when low water and high water occur. The correct way of dealing with the impact of weather on the flow regime of inland waterways is to consider the entire catchment, because the local flow regimes are determined by the weather and the flow regimes in the entire catchment. This is done in research related to the effects of hydrometeorology on hydrology by applying hydrometeorological models, e.g. regional climate models and hydrological ones, to the entire river catchment. Currently, flood protection is not limited to the observation of only one location; water level observations of several gauge stations and meteorological information about the global and local development of the weather serve as input to giving e.g. a flood alert.

Weather related phenomena having a significant effect on inland waterway transport and inland waterway infrastructure are high water, low water, ice, visibility and wind, the latter two being of minor importance.

The following shows qualitative and as far as possible also quantitative thresholds for inland waterway transport.

Table 12. Threshold values for inland waterway.

Heavy precipitation (high water)

Threshold	**Impacts**	**Consequences**
> Highest Navigable Water Level (HNWL) or HNWL + 90 cm (in Austria); the threshold value is locally different providing the responsible authorities with a tentative criterion for decision making.	High discharge, high water levels, high flow velocities, changes in sediment transport, occurrence of driftwood, local aggradation, degradation and scour.	Inland waterway transport: Usually, suspension of navigation, delays, vessel damage (e.g. propulsion devices). Infrastructure: Modification of river and bank morphology, possible damage to and clogging or sedimentation of navigation signs, gauges, ramps and stairs, berths, banks, towpaths, port and lock areas, dams, groins and training walls.
> HWL30 (water level according to a 30-year level of discharge HQ30).	High discharge, high water levels, high flow velocities, changes in sediment transport, occurrence of driftwood, local aggradation, degradation and scour.	Inland waterway transport: suspension of navigation, delays, vessel damage (e.g. propulsion devices). Infrastructure: Modification of river and bank morphology, possible severe damage to and clogging or sedimentation of navigation signs, gauges, ramps and stairs, berths, banks, towpaths, port and lock areas, dams, groins and training walls, flooding of areas protected against HWL30.

> HWL100 (water level according to a 100-year level of discharge HQ100 = often design water level related to flood protection) + freeboard (approx. 0.5 – 1.0 m, depending on the location).	Very high discharge, very high water levels, very high flow velocities, changes in sediment transport, occurrence of driftwood, local aggradation, degradation and scour.	Inland waterway transport: Suspension of navigation, delays, vessel damage (e.g. propulsion devices). Infrastructure: Modification of river and bank morphology, possible severe damage to and clogging or sedimentation of navigation signs, gauges, ramps and stairs, berths, banks, towpaths, port and lock areas, dams, groins and training walls, catastrophic flooding of protected areas.
Weather constellations of August 2002 (severe threshold), July and August 2005 and January 2004.	High discharge, high water levels, high flow velocities, changes in sediment transport, occurrence of driftwood, local aggradation, degradation and scour.	Inland waterway transport: Usually, suspension of navigation, delays. Infrastructure: Modification of river and bank morphology, possible damage to and clogging or sedimentation of navigation signs, gauges, ramps and stairs, berths, banks, towpaths, port and lock areas, dams, groins and training walls.
Weather constellation of January 2003 as occurred in the Elbe region.	High discharge, high water levels, high flow velocities, changes in sediment transport, occurrence of driftwood, local aggradation, degradation and scour, occurrence of ice and ice jams.	Inland waterway transport: Suspension of navigation, delays, vessel damage (e.g. propulsion devices). Infrastructure: Modification of river and bank morphology, possible severe damage to and clogging or sedimentation of navigation signs, gauges, ramps and stairs, berths, banks, towpaths, port and lock areas, dams, groins and training walls, danger of dam overflow and catastrophic flooding of protected areas.

Drought

Threshold	Impacts	Consequences
Weather constellation of 2003, in particular of the summer of 2003 (June, July, August); accumulation and stability of anti-cyclone weather conditions.	Locally low discharge, low water levels, low flow velocities; mainly in free flowing sections; canalized sections are much less affected.	Inland waterway transport: reduced cargo carrying capacity of vessels, increased power demand due to shallow water resistance, increased sailing times and delays due to shallow water resistance, possibly interruption of navigation Infrastructure: Changes in sedimentation processes.

Temperatures below 0^{o}C

Threshold	Impacts	Consequences
Weather constellations of the winters of 1996/97 (= severe threshold), 2005/2006 and 2008/2009.	Local appearance of ice and ice jams.	Inland waterway transport: Suspension of navigation; navigation at own risk due to missing navigation signs damaged by ice. Infrastructure: Possible damage to navigation signs and infrastructure.

Fog, snow and rainfall

Threshold	Impacts	Consequences
Reduced visibility = decision of the master of a vessel (formerly < 1 km according to CEVNI 2007).	Reduced speed, interruption of navigation of vessels without radar.	Inland waterway transport: Delay.

Wind

Threshold	Impacts	Consequences
18 m/s for large motor cargo vessels (110 m x 11.4 m x 3.1 m) carrying containers, and pushed convoys in ballast without bow thrusters in the Danube region close to the Iron Gates.	Increased side forces on vessels and cargo on deck, increased heel and rolling, reduced manoeuvrability.	Inland waterway transport: Possible sliding of empty unlashed containers on deck and loss of cargo, suspension or interruption of navigation, flooding of cargo holds and loss of stability, capsize, accidents, increased maintenance, increased time for manoeuvring operations, delay. Infrastructure: Possible damage due to collisions, increased maintenance.

5.3.2.5 Thresholds for road and railway infrastructures

Table 13. Threshold values for road and rail infrastructures.

Precipitation		
Threshold	**Impacts**	**Consequences**
≥ 100 mm/48 h	Lower road network: landslides, erosion, bridge damages	Rebuilding, delays in traffic[4]
≥ 150 mm/24 h	Regional foods, landslides, erosion	Road closed 1–6 days. Underpasses under water, delays in traffic[5]

5.3.3 Threshold values covered by the European Severe Storms Database

The European Severe Weather Database (ESWD) covers the following definitions of severe weather types:

Table 14. ESWD threshold values for severe weather.

Weather type	Definition	Significant
HAIL – severe hail fall	Hailstones observed having a diameter (in the longest direction) of 2.0 cm or more, or smaller hailstones that form a layer of 2.0 cm thickness or more on flat parts of the earth's surface. Remark: The hailstones of a hail layer should not have been accumulated because of transport by water, wind or by any other means.	Hail with diameter of 5 cm or more is called "significant".
PRECIP – heavy precipitation	Damage caused by excessive precipitation is observed, or no damage is observed but precipitation amounts exceptional for the region in question have been recorded, or one of the following limits of precipitation accumulation is exceeded: 30 mm in 1 hour, 60 mm in 6 hours, 90 mm in 12 hours, 150 mm in 24 hours.	
WIND – severe wind gust	Measured wind speeds of 25 m/s or higher, or wind damage inflicted by winds that were likely stronger than 25 m/s.	Damaging winds with 33 m/s or more (F1 or more on the Fujita scale) are called "significant".

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[4] Direct rebuilding costs on average 175 k€ per incident according to Finnish estimates; applicable only in Finland.

[5] Direct rebuilding costs on average 400 k€ per incident according to Finnish estimates; applicable only in Finland.

TORNADO – tornado, waterspout	A vortex, typically from a few metres to a few kilometres in diameter, extending between a convective cloud and the earth's surface, which may be visible by condensation of water vapour or by material (e.g. dust or water) being lifted off the earth's surface.	Tornadoes with F2 or more on the Fujita scale are called "sigz".
FUNNEL – funnel cloud	A vortex, typically from a few metres to a few tens of metres in diameter, extending downward from a convective cloud but not reaching the earth's surface, that is visible by condensation of water vapour, normally having a cone or tube shape. Remark: Funnel clouds and weak tornadoes can be easily confused if the tornado funnel does not fully extend to the ground, e.g. due to lack of boundary-layer moisture. If there is any evidence that the vortex had ground contact, the event should be reported as a tornado.	
GUSTNADO – gust front vortex (gustnado)	A vortex occurring along the gust front of a convective storm and being visible by material that is lifted off the earth's surface, typically from a few metres to a few tens of metres in diameter, extending from the earth's surface upward but not extending to a cloud.	
DEVIL – dust- or sand devil (land devil) or steam devil (water devil)	A vortex not associated with a convective storm, typically from a few metres to a few tens of metres in diameter, extending upward from the earth's surface but not reaching any cloud, visible by material that is lifted off the earth's surface or by water droplets. Remark: Devils (lesser whirlwinds) result from temperature differences between the surface and the air above. Whirls in the lee of objects, which may meet the criteria above are dynamically driven and are not considered devils.	

5.4 Linking weather phenomena with transport system indicators

Table 15 presents an example of key weather phenomena in Scandinavia, their impacts and main consequences to the different parts of the transport system, namely to infrastructures, passenger and logistic services and operations. This kind of table is proposed to be constructed, and complemented with threshold values identified for each of the climatic zones as well as preparedness of different countries, in the forthcoming phases of the EWENT project (WP3–WP5).

Table 15. The most significant weather phenomena and their consequences to transport system infrastructures and services (=indicators describing consequences to the transport system).

ROAD TRANSPORT				
Phenomena	***Impacts***	***Consequences to infrastructure***	***Consequences to passenger transport services, operations***	***Consequences to logistic services, operations***
Snowfall	• Flooding • Avalanche • Poor visibility • Slippery road surface.	• Erosion of construction material (damage to pavement [km^2]; damage and collapse of culvert and drainage pipe → blocking of drainage systems [km]) • Water on road and in underground systems [km] • Destruction of road infrastructure [km] • Damage to bridge support [km^2] • Destruction of bridge [km^2] • Destruction of embankments and slopes [km^2].	• Sliding, snowdrift→ slower driving speeds → congestion → delays [h/min] • Road blocks, etc. (accidents [number of dead and injured persons]; material damage to vehicles, equipment and infrastructures [€]; slower driving speeds → congestion → delays [h/min]) • Changes in accessibility of e.g. basic daily services, terminals [km, min] • Changes in quality of transport services e.g. frequency, routes, waiting times, predictability, information, etc. [min, km].	• Sliding, snowdrift→ slower driving speeds → congestion → delays [h/min] • Road blocks, etc. (accidents [number of dead and injured persons]; material damage to vehicles, equipment and infra- structures [€]; slower driving speeds → congestion → delays [h/min]) • Changes in accessibility of e.g. terminals [km, min] • Changes in quality of logistic services e.g. reliability, accuracy, information, etc. [min, km].
Heavy Precipitation	• Landslides • Mud flow • Poor visibility • Slippery road surface.	• Erosion of construction material damage to pavement [km^2]; damage and collapse of culvert and drainage pipe → blocking of drainage systems [km] • Water on road and in underground systems [km] • Destruction of road infrastructure [km] • Damage to bridge support [km^2] • Destruction of bridge [km^2] • Destruction of embankments and slopes [km^2].	• Slower driving speeds → congestion → delays [h/min] • Changes in accessibility of e.g. basic daily services, terminals [km, min] • Changes in quality of transport services e.g. frequency, routes, waiting times, predictability, information, etc. [min, km] • Accidents [number of dead and injured persons] • Material damage to vehicles, equipment and infrastructures [€].	• Sliding (accidents [number of dead and injured persons]; material damage to vehicles, equipment and infrastructures [€]) • Slower driving speeds → congestion → delays [h/min] • Changes in accessibility of e.g. terminals [km, min] • Changes in quality of logistic services e.g. reliability, accuracy, information, etc. [min, km] • Accidents [number of dead and injured persons] • Material damage to vehicles, equipment and infrastructures [€].

Wind gusts	• Falling trees • Changes in sea level, flooding • Vehicle behaviour.	• Erosion of construction material (damage to pavement [km^2]; damage and collapse of culvert and drainage pipe → blocking of drainage systems [km]) • Water on road and in underground systems [km] • Destruction of road infrastructure [km] • Damage to bridge support [km^2] • Destruction of bridge [km^2] • Destruction of embankments and slopes [km^2] • Material damage to equipment and infrastructures [€].	• Accidents [number of dead and injured persons] • Material damage to vehicles, equipment and infrastructures [€] • Slower driving speeds → delays [h/min].	• Accidents [number of dead and injured persons] • Material damage to vehicles, equipment and infrastructures [€] • Slower driving speeds → delays [h/min].
Low temperature	• Flooding • Ice dam • Falling stones from cuttings • Slippery road surface.	• Erosion of construction material (damage to pavement [km^2]; damage and collapse of culvert and drainage pipe → blocking of drainage systems [km]) • Water on road and in underground systems [km] • Destruction of road infrastructure [km] • Damage to bridge support [km^2] • Destruction of bridge [km^2] • Destruction of embankments and slopes [km^2] • Falling stones from cuttings [km^2].	• Slower driving speeds → congestion → delays [h/min] • Changes in accessibility of e.g. basic daily services, terminals [km, min] • Changes in quality of transport services e.g. frequency, routes, waiting times, predictability, information, etc. [min, km] • Accidents [number of dead and injured persons] • Material damage to vehicles, equipment and infrastructures [€].	• Slower driving speeds → congestion → delays [h/min] • Changes in accessibility of e.g. terminals [km, min] • Changes in quality of logistic services e.g. reliability, accuracy, information, etc. [min, km] • Accidents [number of dead and injured persons] • Material damage to vehicles, equipment and infrastructures [€].
Blizzard	• Low temperature + snowfall + wind gust impacts.	• Low temperature + snowfall + wind gust impacts.	• Low temperature + snowfall + wind gust impacts.	• Low temperature + snowfall + wind gust impacts.

RAIL TRANSPORT				
Phenomena	*Impacts*	*Consequences to infrastructure*	*Consequences to services, operations*	*Other*
Snowfall	• Flooding • Freezing • Damage to cables • Loss of electricity • Blowing snow • Blocking of tracks and yards.	• Damage to railway embankment and slope [km, km^2] • Scour of bridge supports [m/km, m^2/km^2?] • Water on track or in underground structures [km] • Damage to rail track [km] • Other material damage to equipment and infrastructures [km, €].	• Stopped and/or cancelled rail services [min/h, €]; delays [min, €] • Inefficient acceleration and braking → slower speeds→delays [h/min] • Accidents [number of dead and injured persons] • Material damage to rail fleet, equipment and infrastructures [€] • Freezing of switches, blocking of railway yard and equipment, snow accumulating on cuttings→slower speeds→ delays [h/min] • Changes in accessibility by train (urban and/or inter-urban) [km, min] • Changes in quality of transport services e.g. frequency, routes, waiting times, predictability, information, etc. [min, km].	• Stopped and/or cancelled rail services [min/h, €]; delays [min, €] • Inefficient acceleration and braking → slower speeds→delays [h/min] • Accidents [number of dead and injured persons] • Material damage to rail fleet, equipment and infrastructures [€] • Freezing of switches, blocking of railway yard and equipment, snow accumulating on cuttings→slower speeds→ delays [h/min] • Changes in quality of logistic services e.g. reliability, accuracy, information, etc. [min, km].
Heavy Precipitation	• Flooding	• Damage to railway embankment and slope [km, km^2] • Scour of bridge supports [m/km, m^2/km^2?] • Water on track or in underground structures [km] • Damage to rail track [km] • Other material damage to equipment and infrastructures [km, €].	• Stopped and/or cancelled rail services [min/h, €]; delays [min, €] • Inefficient acceleration and braking → slower speeds→delays [h/min] • Accidents [number of dead and injured persons] • Material damage to rail fleet, equipment and infrastructures [€] • Changes in accessibility by train (urban and/or inter-urban) [km, min] • Changes in quality of transport services e.g. frequency, routes, waiting times, predictability, information, etc. [min, km].	• Stopped and/or cancelled rail services [min/h, €]; delays [min, €] • Inefficient acceleration and braking → slower speeds→delays [h/min] • Accidents [number of dead and injured persons] • Material damage to rail fleet, equipment and infrastructures [€] • Changes in quality of logistic services e.g. reliability, accuracy, information, etc. [min, km].

Wind gusts	• Changes in sea level; flooding • Damage to cables • Falling trees • Loss of electricity • Freezing • Blocking of tracks.	• Damage to railway embankment and slope [km, km^2] • Scour of bridge supports [m/km, m^2/km^2?] • Water on track or in underground structures [km] • Damage to rail track [km] • Other material damage to equipment and infrastructures [km, €] • Supply cable sag or tensional failure [km, €].	• Stopped and/or cancelled rail services [min/h, €]; delays [min, €] • Inefficient acceleration and braking → slower speeds→delays [h/min] • Accidents [number of dead and injured persons] • Material damage to supply cables, rail fleet, equipment and infrastructures [€] • Freezing of switches, blocking of railway yard and equipment →slower speeds→ delays [h/min] • Changes in accessibility by train (urban and/or inter-urban) [km, min] • Changes in quality of transport services e.g. frequency, routes, waiting times, predictability, information, etc. [min, km].	• Stopped and/or cancelled rail services [min/h, €]; delays [min, €] • Inefficient acceleration and braking → slower speeds→delays [h/min] • Accidents [number of dead and injured persons] • Material damage to rail fleet, equipment and infrastructures [€] • Changes in quality of logistic services e.g. reliability, accuracy, information, etc. [min, km].
Low temperature	• Damage to cables • Loss of electricity • Freezing, frost.	• Overheating of safety device [n, €] • Other material damage to equipment and infrastructures [km, €] • Frost crack, freezing of equipment and structures of track [km, €] • Supply cable sag or tensional failure [km, €]; • Damage to rail track [km].	• Stopped and/or cancelled rail services [min/h, €]; delays [min, €] • Inefficient acceleration and braking → slower speeds→delays [h/min] • Accidents [number of dead and injured persons] • Material damage to supply cables, rail fleet, equipment and infrastructures [€] • Freezing of switches, blocking of railway yard and equipment →slower speeds→ delays [h/min] • Changes in accessibility by train (urban and/or inter-urban) [km, min] • Changes in quality of transport services e.g. frequency, routes, waiting times, predictability, information, etc. [min, km].	• Stopped and/or cancelled rail services [min/h, €]; delays [min, €] • Inefficient acceleration and braking → slower speeds→delays [h/min • Accidents [number of dead and injured persons] • Material damage to rail fleet, equipment and infrastructures [€] • Changes in quality of logistic services e.g. reliability, accuracy, information, etc. [min, km].

Blizzard	• Low temperature + snowfall + wind gust impacts.	• Low temperature + snowfall + wind gust impacts.	• Low temperature + snowfall + wind gust impacts.	• Low temperature + snowfall + wind gust impacts.

WATERBORNE TRANSPORT				
Phenomena	*Impacts*	*Consequences to infrastructure*	*Consequences to services, operations*	*Other*
Wind mean speed	• Pack ice, ice jams.	• Material damage to floating and fitted navigation signs, safety equipment and infrastructures [n, €].	• Stopped and/or cancelled ferry or small vessel services [min/h, €] • Delays [min, €].	• Stopped and/or cancelled ferry or small vessel services [min/h, €] • Delays [min, €] • Changes in quality of logistic services e.g. reliability, accuracy, information, etc. [min, km].
Fog, snowfall and rainfall	• Poor visibility • Changes in sea level.	• Material damage to floating and fitted navigation signs, safety equipment and infrastructures [n, €].	• Stopped and/or cancelled ferry or small vessel services [min/h, €] • Delays [min, €].	• Stopped and/or cancelled ferry or small vessel services [min/h, €] • Delays [min, €] • Changes in quality of logistic services e.g. reliability, accuracy, information, etc. [min, km].
Low temperature	• Pack ice, ice jams • Movements and building up of ice floes by vessels • Breaking up of ice in the springtime.	• Material damage to floating and fitted navigation signs, safety equipment and infrastructures [n, €]. •	• Delays [min, €]. •	• Delays [min, €] • Extra ice braking costs [€] • Changes in quality of logistic services e.g. reliability, accuracy, information, etc. [min, km].
Drought (inland w)				

AIR TRANSPORT				
Phenomena	*Impacts*	*Consequences to infrastructure*	*Consequences to services, operations*	*Other*
Heavy precipitation	• Route blocked • Airport closed • Damage of a/c & APT • Loss of situational awareness.	• Material damage to ground structures [km^2, €].	• Delays • Cancellations • Diversion • Accidents • Incidents.	
Heavy snowfall	• Runways blocked		• Delays	
Low visibility, associated with cloud, mist, fog, snow	• Separation between aircraft and airport increased • Airport closed.	• Material damage to ground structures [km^2, €].	• Delays • Cancellations • Diversion • Accidents • Incidents.	
In-flight icing, ground icing	• Icing of the body, the outer skin, air intakes, bend, carburettor sensing devices, air conditioning.		• Changes in flight characteristics and lift/drag characteristics • Changes in functionality of certain components (like the engine) • Loss of control • Delays • Diversion. • Accidents • Incidents.	

Wind	• Head wind • Tail wind • Cross wind/gust.	• Material damage to ground structures [km^2, €].	• Reduced ground speed • Reduced lift / moderate take-off, landing • Reduced runway capacity, • Ground strike, too fast • Delays • Accidents • Incidents.	
Thunderstorms and lightning, hail	• Route blocked • Airport closed • Damage of a/c & APT • Loss of situational awareness.	• Material damage to ground structures [km^2, €].	• Delays • Cancellations • Diversion • Accidents • Incidents.	
Sandstorm, volcanic ash	• Airspace closed	• Erosion of engines	• Delays • Cancellations • Diversion.	
Turbulence	• Flight altitude changes • Variations in airspeed • Loss of a/c control.		• Passenger discomfort • Structural damage • Delays • Cancellations • Accidents • Incidents, injuries.	
Blizzard	• Low temperature + snowfall + wind gust impacts.	• Low temperature + snowfall + wind gust impacts.	• Low temperature + snowfall + wind gust impacts.	• Low temperature + snowfall + wind gust impacts.

LIGHT TRAFFIC				
Phenomena	*Impacts*	*Consequences to infrastructure*	*Consequences to services, operations*	*Other*
Snowfall, icy rain	• Slippery sidewalk surfaces.		• Falling accidents.	

6. Sum-up and discussion

6.1 Scope and limitations

This report's main results comprise the following:

- A list of critical weather phenomena which, on the basis of literature and media mining, are clearly such that they have consequences on transport systems
- Threshold values of parameters for the above phenomena which, if met or exceeded, indicate a high probability of measurable harmful impacts and consequences
- Selected impact mechanisms (12) that indicate why certain impacts and consequences start to occur; the meaning of these causal maps is to help later in the identification of efficient mitigation and adaptation measures. For example, in some cases just improving drainage could be a very efficient strategy, or in other cases there is little to do except improve the dissemination of information. Identification of efficient measures will be part of the following EWENT work packages.

Although this report is not intended to go beyond the above, in this summary we identify some additional potential cases of use. It is up to the transport system stakeholders to take it from there. This report contains, we believe, a substantial amount of new information, but it needs to be scrutinized by each recipient in view of the immeasurable variation in the multiple needs of stakeholders.

6.2 Results in a nutshell

Weather indeed has major impacts. This report used three different approaches to assess the impacts and consequences extreme weather phenomena have on the transport system. First, there was the traditional review of professional literature. Second, media mining was done in order to get more empirical data and to assess which modes in which parts of Europe seem to be affected the most. Third, there was a compilation of specific case studies on past extreme incidents, helping to assess the specific consequences of certain phenomena.

All aspects and functions of the transport system are affected, but in different ways in different parts of Europe and on different time scales when impacts are distinguished between operations and infrastructure. Operations can always be more or less flexibly adapted to a changed situation, but infrastructure requires long-term planning if modifications concerning weather resilience are to be achieved.

The researcher group tried to point out the most relevant weather phenomena, which on the basis of media reports, literature and case studies seem to impact the transport system the most. This summary can be regarded as an empirical-heuristic conclusion: empirical in the sense that it relies on past events and recorded incidents and studies; heuristic in the sense that it cannot be claimed that there will not be other, even more attention-requiring phenomena – it is simply the current presumption of the research group.

This report concludes with an “extreme weather impact map”, which is definitely an oversimplification but is nonetheless adopted to visualize where the top priorities are and what type they should be.

The consequences are prioritised as follows:

1st priority:	Accidents leading to casualties and injuries (A)
2nd priority:	Infrastructure collapse or damage (I)
3rd priority:	Time delays (T)
4th priority:	Sub-optimal operations (O).

The weather phenomena symbolised on the map are those identified as the most common extremes with identifiable consequences, i.e. heavy rain, heavy snowfall, extreme winds, extreme heat, drought, and visibility.

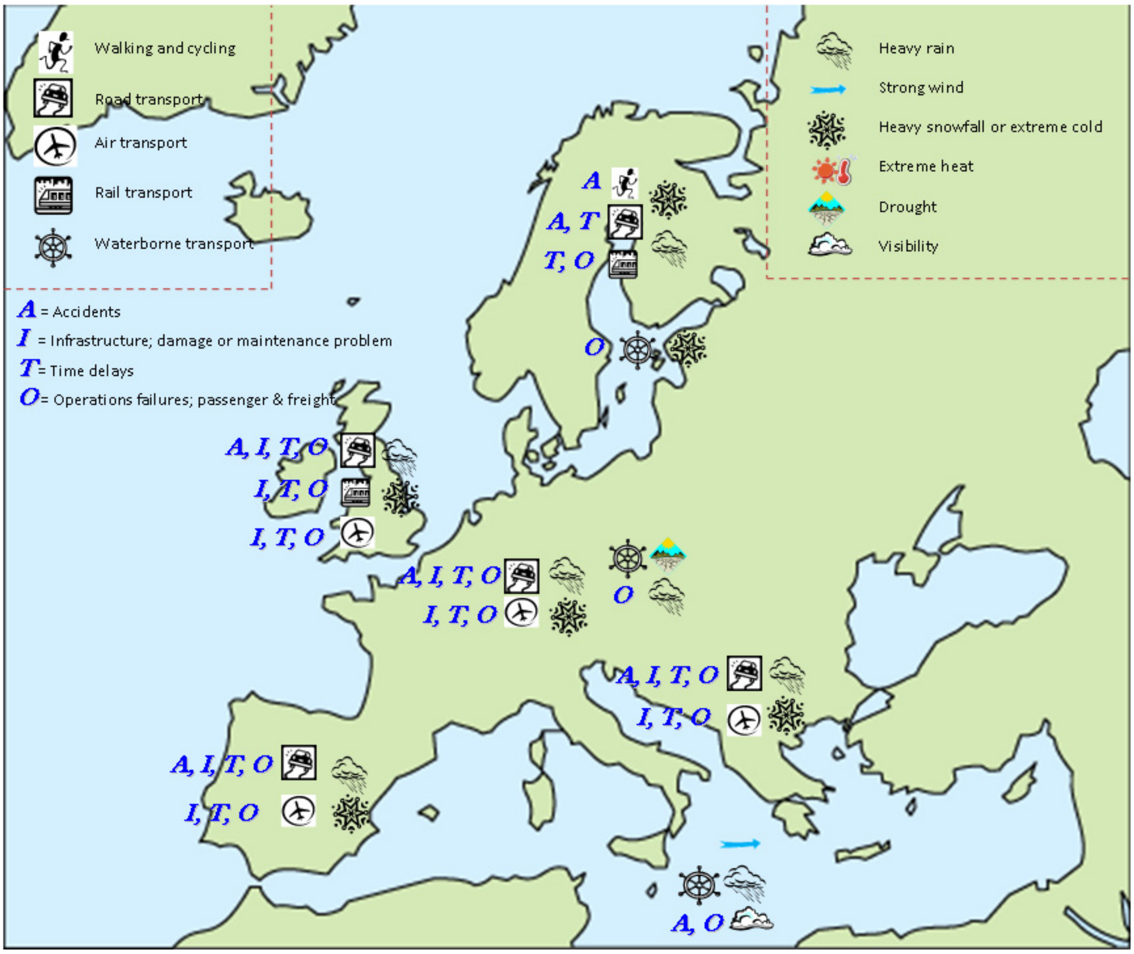

Figure 16. Sum-up of critical weather phenomena, their occurrence by region where effects are the most severe, with the most affected modes of transport and the consequences.

The map is of course a crude simplification that simply points out what the most urgent problems seem to be in different parts of Europe. Its purpose is to give an overall impression and it cannot be used beyond this simple purpose or regarded as one of the main findings presented at the start of this chapter.

Identifying the most critical phenomena on the basis of gathered information is relatively easy: precipitation in all its forms very quickly affects all land transport modes and when precipitation comes as snow, aviation is likewise affected. Precipitation also affects inland waterway transport operations significantly. For land transport modes, precipitation has a similar type of impact in all regions. Excessive rain and snow also block urban transportation more effectively than any other weather phenomena.

When heavy snowfall is encountered, the only essential difference between regions is the availability of snow removal and maintenance equipment (and studded tyres in the Nordic countries in winter). Furthermore, especially snow and ice cause severe road accidents, the consequences of which should be considered top priority. This being the case, the greatest responsibility for mitigating the above effects probably falls on the owners and managers of the road infrastructure. How effectively they will in the end be able to answer this challenge in terms of their resources and preparedness is another matter.

Precipitation is the phenomenon that most likely has the severest impacts on transport infrastructures, in particular on road and rail embankments. Even relatively modest but frequent flooding quickly deteriorates land structures over the years, although one single event does not in itself appear to be very serious.

Road transportation seems to be the most vulnerable mode. There are self-evident reasons for this. First, the traffic volumes are highest on roads and the capacity usually most limited in densely populated areas. One relatively insignificant crash can quickly create chaos on urban motorways. The second reason is that road traffic is least controllable and manageable. Where air control or a railway traffic management centre can quickly decide on and execute adaptive and corrective measures, road traffic remains mostly a slowly self-adaptive system that is geographically widespread and scattered.

As to climatologic regions, most of the reported cases from both the literature and media reports seem to come from mainland Europe, the UK and Scandinavia. Most likely this is partly dependent on a) active research and b) active media in those regions. In this sense, the summary of results could underestimate weather phenomena such as heat waves and sand storms, which are common in southern parts of the EU. This bias is considered, however, to be insignificant in terms of the overall conclusions.

6.3 Initial thoughts on mitigation and adaptation

The following thoughts are very tentative and should be considered only as input material for the continuation of EWENT.

Two tentative strategic options seem to arise and be distinguishable in a broad sense for decision makers responsible for adapting to and mitigating extreme weather consequences. Either we can focus our efforts on those modes and places that are already quite well controlled, such as railways and aviation, and ensure that their resilience to extreme weather is enhanced. These modes can then serve as back-up systems when other modes (roads) fail to be of service. This could well be a cost-efficient and resource-efficient option from the society’s point of view.

Or, we can start working on the road mode, trying to increase its resilience in different ways such as improving maintenance preparedness and road traffic control and information services. The vehicle manufacturing industry has already been active in developing anti-skid systems that are definitely useful in cases of icy and snowy roads. Relying on driver supporting systems and information services probably puts the onus (both effort and cost) on the users rather than on the public sector.

The above options are, however, very preliminary thoughts how the battle against extreme weather impacts could be envisioned. For both strategies, if they now at all are excluding options from one another, there are both pros and cons (Table 16). These are summarised and evaluated in the below table. If both fronts are battled simultaneously, there is a risk of dividing the efforts and resources inefficiently. This risk is enhanced, when international, joint efforts are considered.

Table 16. Pros and cons of alternative strategic emphasis.

Strategic emphasis	**Pros**	**Cons**
Road system resilience	Much of the cost can be borne directly by the users, because users pay for in-vehicle safety systems and possibly also partly for information services. The road system is the most “connecting” mode of transport – its reliability also serves the other modes best.	Investing in maintenance equipment and more comprehensive traffic management is expensive and possibly not a very cost-efficient strategy. The road system is a scattered system that is complex to manage and control.
Rail and aviation system resilience	Rail and aviation systems are concentrated and centralised and manageable. Mitigation and adaptation strategies are more easily implemented in centralised systems. Aviation infrastructure owners and the aviation industry are obliged to bear much of the cost (which are then passed on to the consumer).	Both industries are in an economic pinch and introducing more obligations might further aggravate their situation. For the rail sector some measures might require large public investments, which could be difficult to justify for a sector that already enjoys some public financial support. Both rail and air travel chains almost without exception include stretches on roads and streets.

Inland waterways and short-sea shipping are special cases, and without underestimating their importance they are probably in a better position to meet extreme weather events. Their share of the transportation market could even be increased and improved by recognising them as more weather-resilient modes that have greater reliability.

6.4 Making use of the results

There are multiple ways in which to exploit the results of this report. The first is purely meteorological, as the threshold values for weather phenomena that can and probably will cause damage and interruptions to the functioning of the transport system. Meteorological service providers and public safety authorities can make use of the list of threshold values and adjust them to their specific needs and naturally to those of the public. A better understanding of the consequences of extreme weather events will help improve services and make it clearer to users of public and transport systems what can be expected when extreme weather is about to hit.

Transport system stakeholders, infrastructure managers, maintenance contractors, operators and transport service providers can benefit as well. A clear perception of how extreme weather can influence their operations and service needs is essential when more precise planning and operational preparedness is both a business success factor and a social necessity. Actually there is little excuse not to be prepared, once the information and empirical knowledge is available.

Right from the start of the EWENT project, the insurance sector was one of the identified beneficiaries of the project's results. The extreme weather parameter list with its threshold values provides an input for statistical models and planning of insurance strategies. The impact mechanisms devised and shown in Appendix B might prove to be useful when creating policies and rules for fair and just compensation.

Finally, we believe that the field of infrastructure engineering can use the list, if it finds it value-adding, to review weather resilience standards for different infrastructures.

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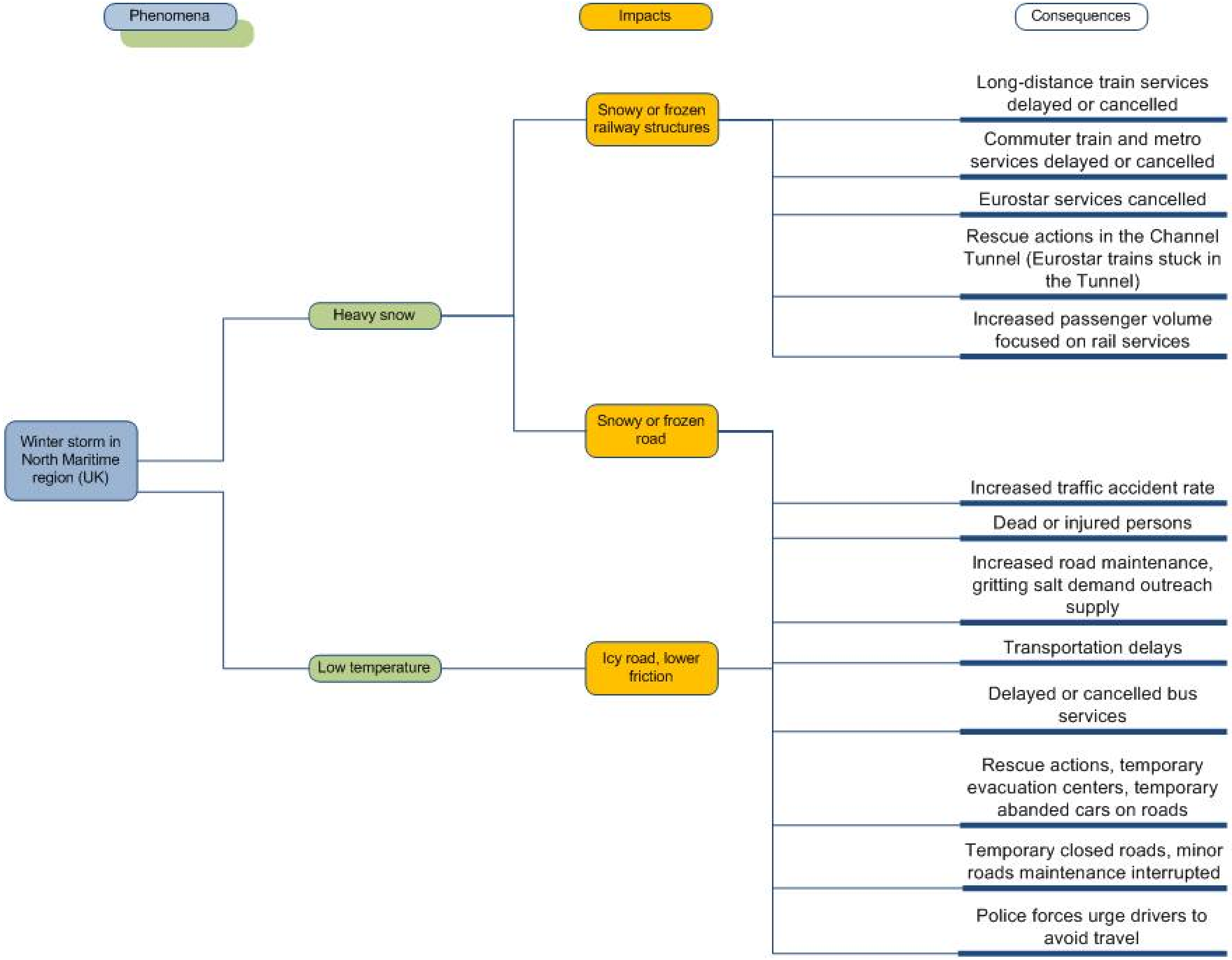
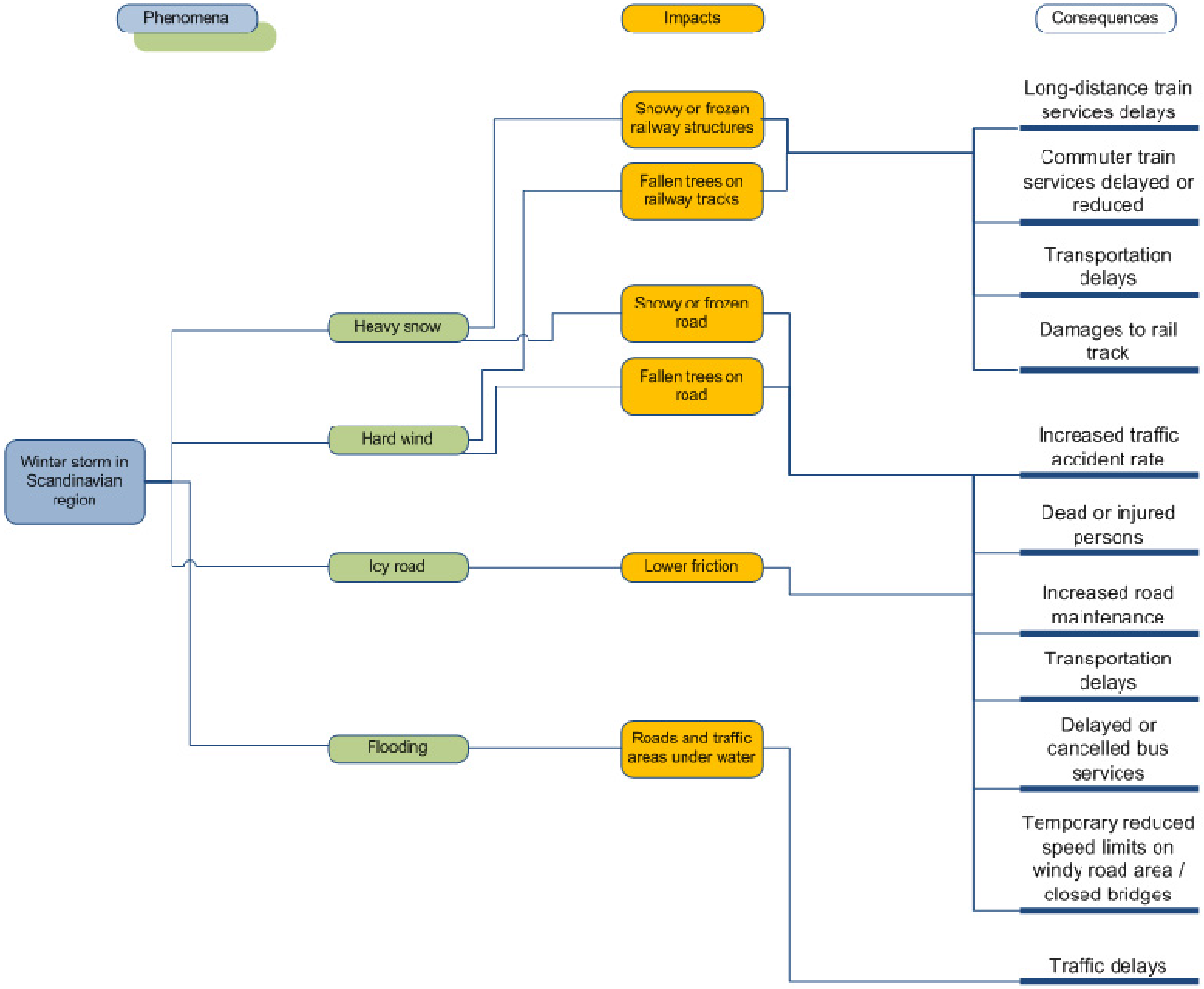
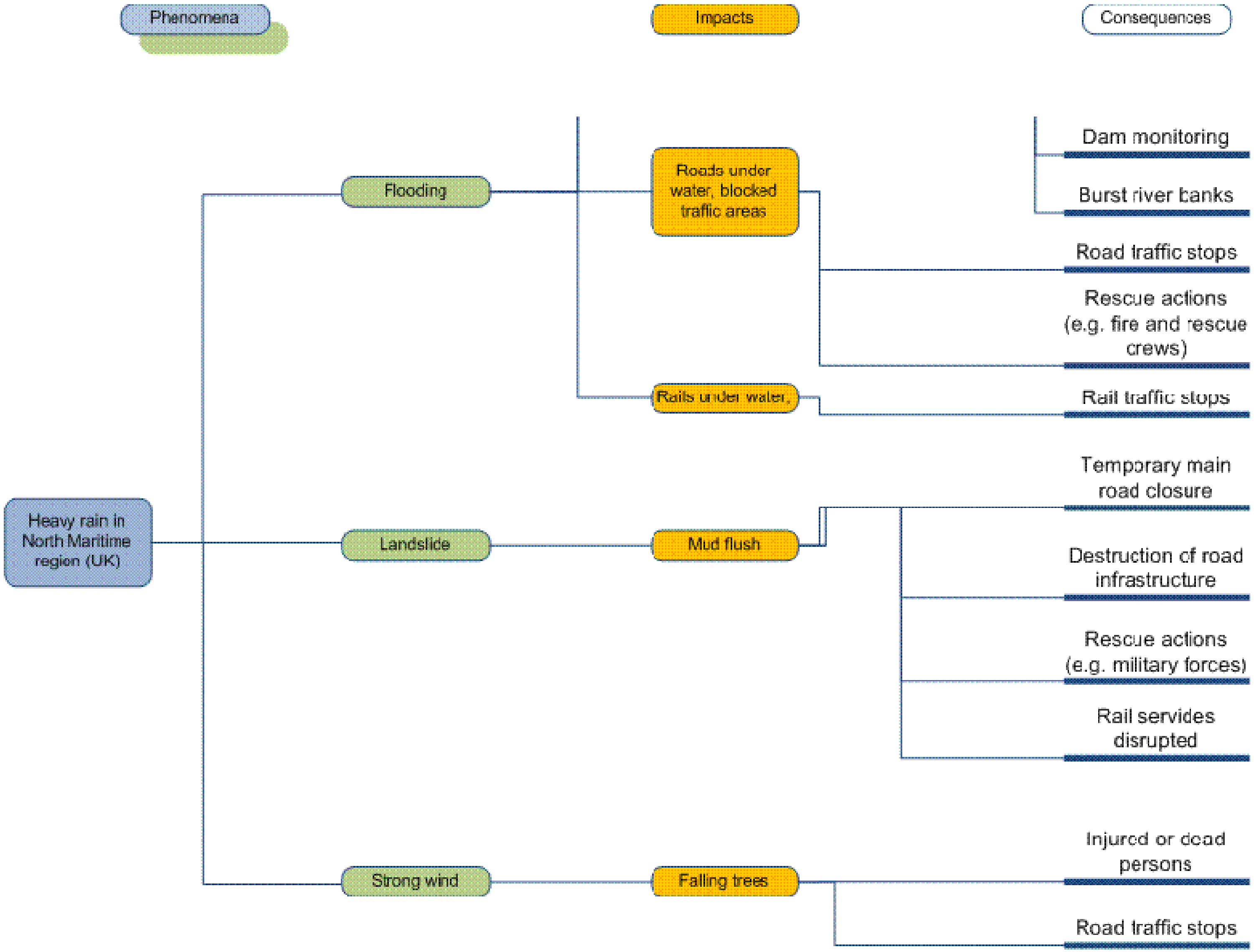
Appendix A: Media database – an excerpt

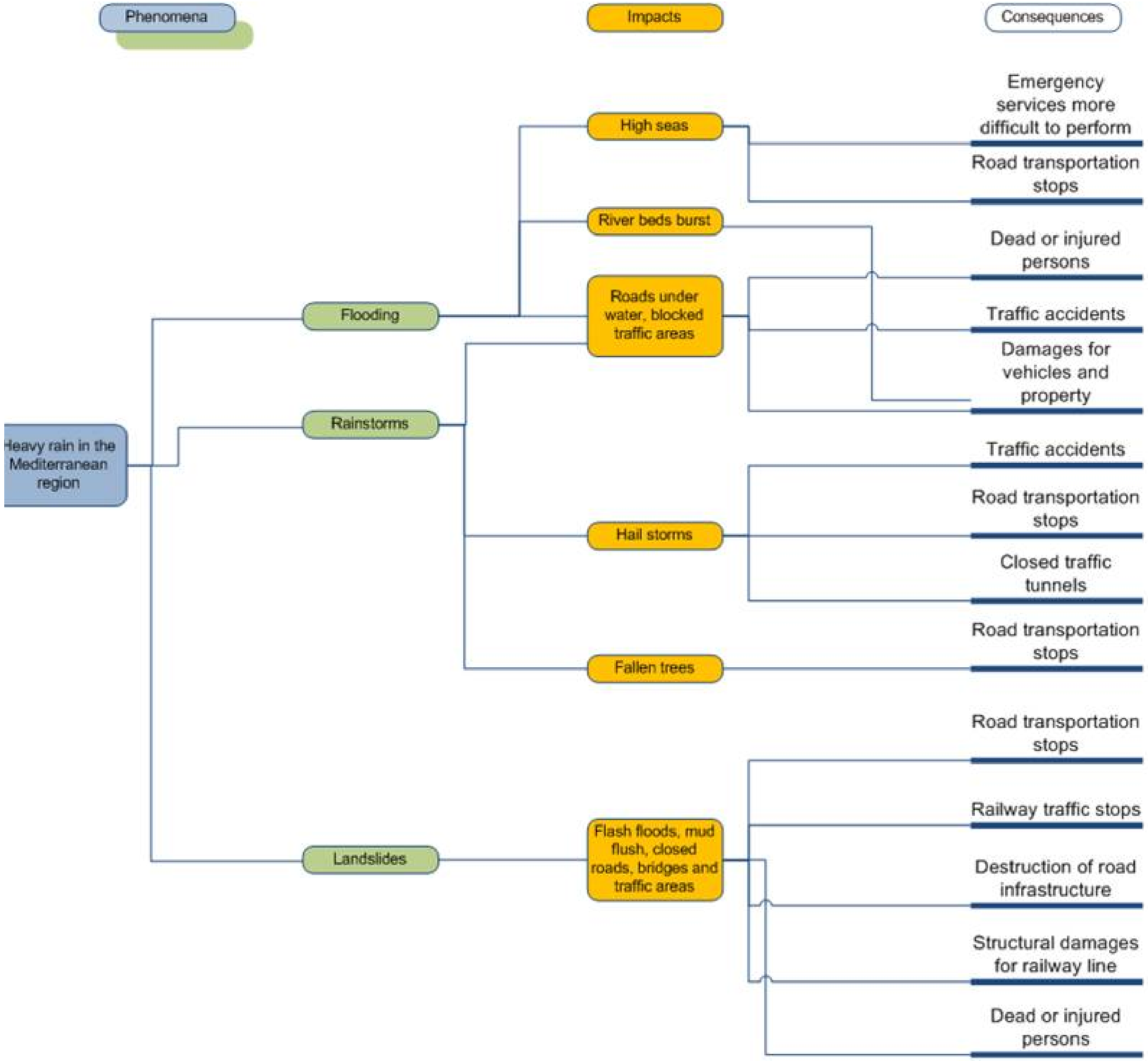
EVENT date	Event A	Weather parameters	Country	Infrastructure	Comments A	Comments B	Consequences	Date added	URL(s)
21.7.2007	Heavy rain		United Kingdom	Roads		flooding 3,000 million $ insured losses	In Britain, hundreds of motorists were stranded in their cars on a major highway after one of the biggest downpours of an already wet summer.	10.8.2010 via donau complement	http://www.reuters.com/article/idUSL2151039120070723
24.7.2007	Temp. - high		Croatia	General	Note: traffic jams not affected by extreme weather events?		Croatian Red Cross volunteers have taken to the roads and highways to distribute bottled water to thousands of motorists stuck in long queues of vehicles under the burning sun, on their way to holiday resorts on the Adriatic coast. The Croatian Red Cross has made available 100,000 bottles of water which are being distributed at critical locations such as entrances to tunnels and highway exit ramps.		http://www.ifrc.org/docs/news/07/07072401/
25.7.2007	Temp. - high	46 degrees Celsius	Greece	Roads			The heat wave caused a spike in smog pollution in Athens, with ozone levels above emergency limits in several districts, prompting the government to urge motorists to avoid the city centre.		http://www.terradaily.com/reports/Heatwave_Turns_Southeastern_Europe_Into_Tinderbox_As_Fires_Rage_999.html http://rawstory.com/news/afp/Heatwave_turns_southeastern_Europe__07252007.html
29.7.2007	Temp. - high		Spain	Rail	Many forest fires in areas of Málaga, Córdoba and Sevilla. The reason for fires has been the overheating of the projectile, which laid in the shooting field. Ecologistas are acusing the militars.		The railway between Ronda and Benaoján needed to be cut and also in some moments the higway A-376, between Ronda and Sevilla.	27.7.2010	http://www.elpais.com/articulo/andalucia/Varios/incendios/forestales/afectan/Cordoba/Ronda/Sevilla/elpepuespand/20070729elpand_4/Tes
7.8.2007	Heavy rain	173l/m^2 in 24h (Fehmarn)	Germany	Inland shipping	07.-11.08 **LEANDER** Rhine, Ruhr	flooding also in Switzerland	Flood wave on river Rhine. Ceased inland shipping between Lake Constance and Karlsruhe for several days. Airport Berlin Tegel closed after heavy storm	27.8.2010 via donau	
8.8.2007	Heavy rain		Switzerland	Roads	8. - 9.8 Also in Italy and Germany	**Swiss re: the 15th costly insurance losses in 2007** **1 victim**	Heavy rain in Switzerland. This caused floods of many rivers, train delays and difficulties on many streets.		http://de.euronews.net/2007/08/09/unwetter-und-ueberschwemmungen-in-der-schweiz/
22.8.2007	Heavy rain	185 litres of water per square metre in Nerja	Spain	Roads			Heavy rain in south part of Spain has cut some roads. Lot of flooding on roads.Many trees fell over the bus station of Granada. 185litres of water per square metre in Nerja.		http://www.alertatierra.com/Torm0907.htm
23.8.2007	Heavy rain	52 litres of water per square metre	Spain	Roads			52 litres of water per square metre. The Mijas Costa water park was evacuated as a precautionary measure with some cars getting trapped in mud and needing the services of a tow truck to get out. Many trees fell onto parked cars in Fuengirola, and there was traffic chaos in many areas.		http://www.typicallyspanish.com/news/publish/article_12124.shtml#ixzz0htgTTWOq
7.9.2007	Heavy rain		Romania	Rail			Flood due to heavy precipitation in 4 counties in the eastern part of Romania. 4 people died, many houses were destroyed Electric power cuts, 8 rail lines were closed , roads were damaged and covered by debris and water, several bridges also damaged, delays in road and rail tamsportation.		http://www.curierulnational.ro/Eveniment/2007-09-07/Inundatiile+fac+ravagii+in+Moldova.+Se+anunta+ploi+in+continuare
11.10.2007	Fog		United Kingdom	Ocean/Sea traffic			A coach, a tanker and eight other vehicles were involved in the accident which happened in fog at 0400 BST. A coach passenger suffered fatal head injuries. Another man underwent surgery for whiplash and arm injuries. A further 18 people went to hospital themselves and were later discharged, including one person who had suffered chest injuries		http://news.bbc.co.uk/2/hi/uk_news/england/london/7040209.stm
16.10.2007	Heavy rain		Spain	Roads	Also hrbour / logistic		Granada region: The rainstorm brought hail with it in Pinos Puente, where a rock fall closed the N-432, and the A-92 was also closed to traffic between Loja and Salar for some four hours early on Tuesday morning.		http://www.typicallyspanish.com/news/publish/article_13058.shtml#ixzz0htfuk38i
7.11.2007	Strong wind	60 mph	United Kingdom	Ocean/Sea traffic	Tilo 7.-8.11.2007	UK, Ireland, Netherlands	In the Netherlands, the Eastern Scheldt storm surge barrier and the gigantic Maeslantkering (sealing off the Rotterdam harbor) were closed. For the first time since 1976, the entire coastline was put on alert and under round-the-clock surveillance. The tidal surge traveling down the North Sea	29.7.2010 RM	http://wapedia.mobi/en/European_windstorm

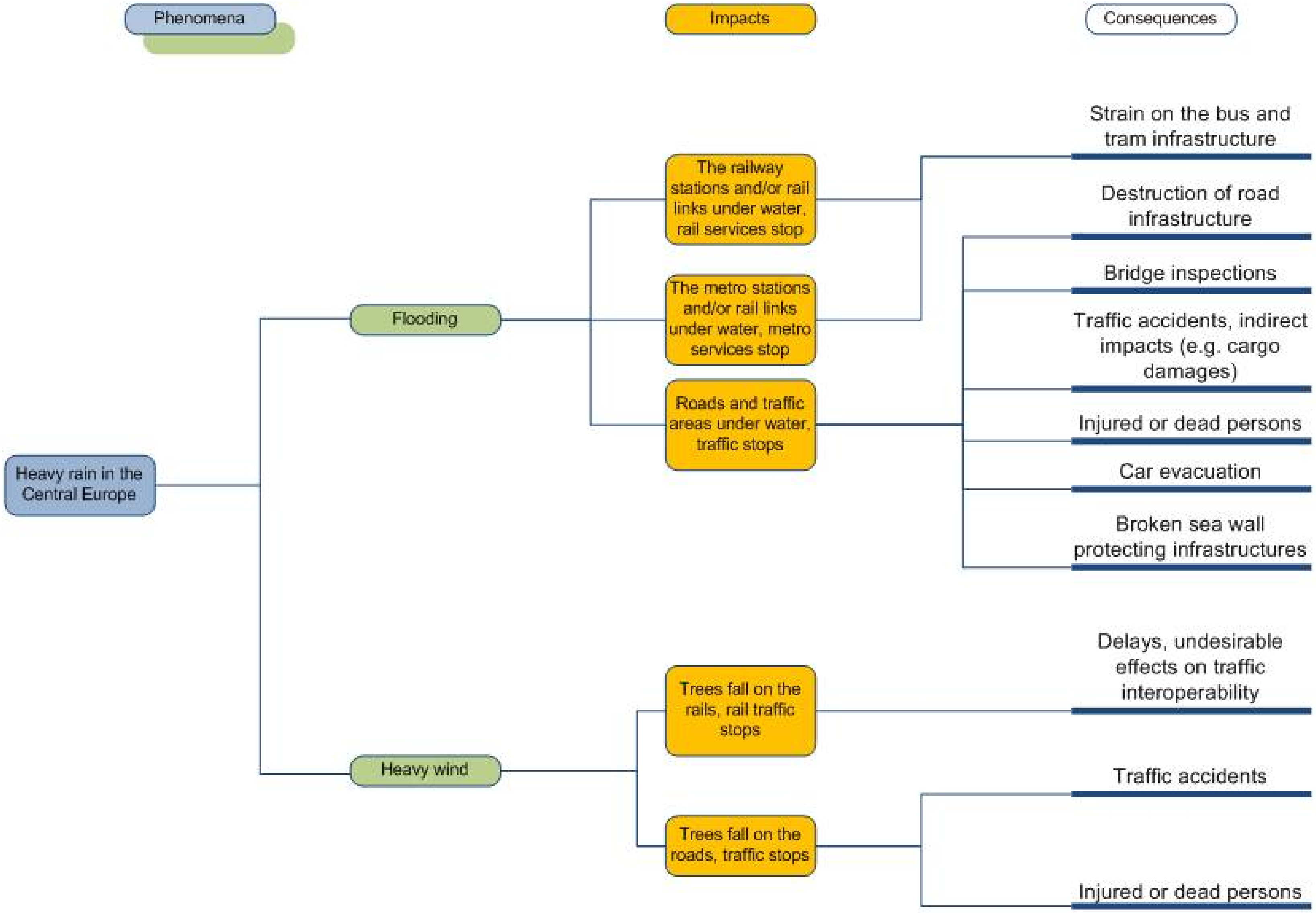
Appendix B: Causal diagrams

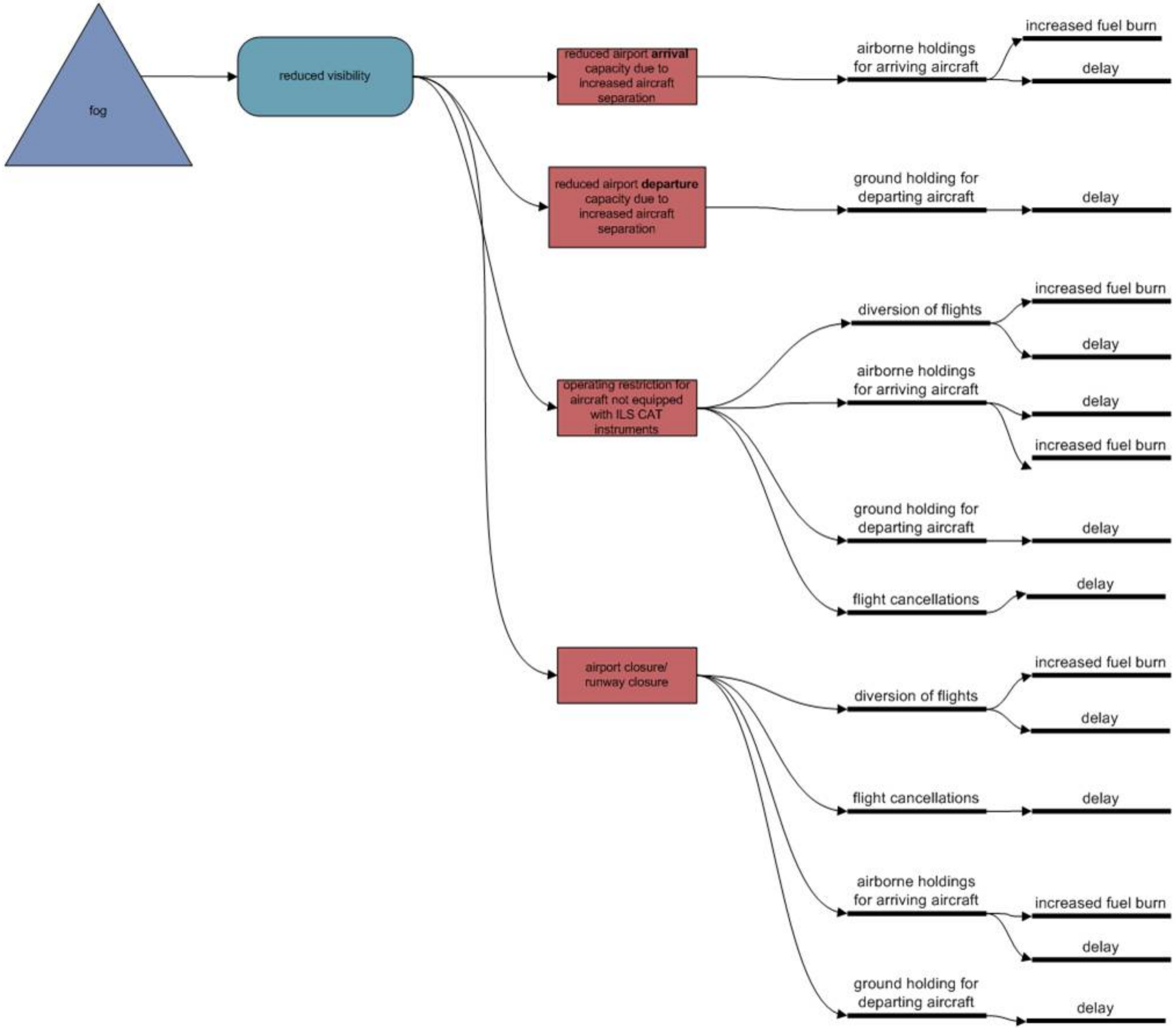


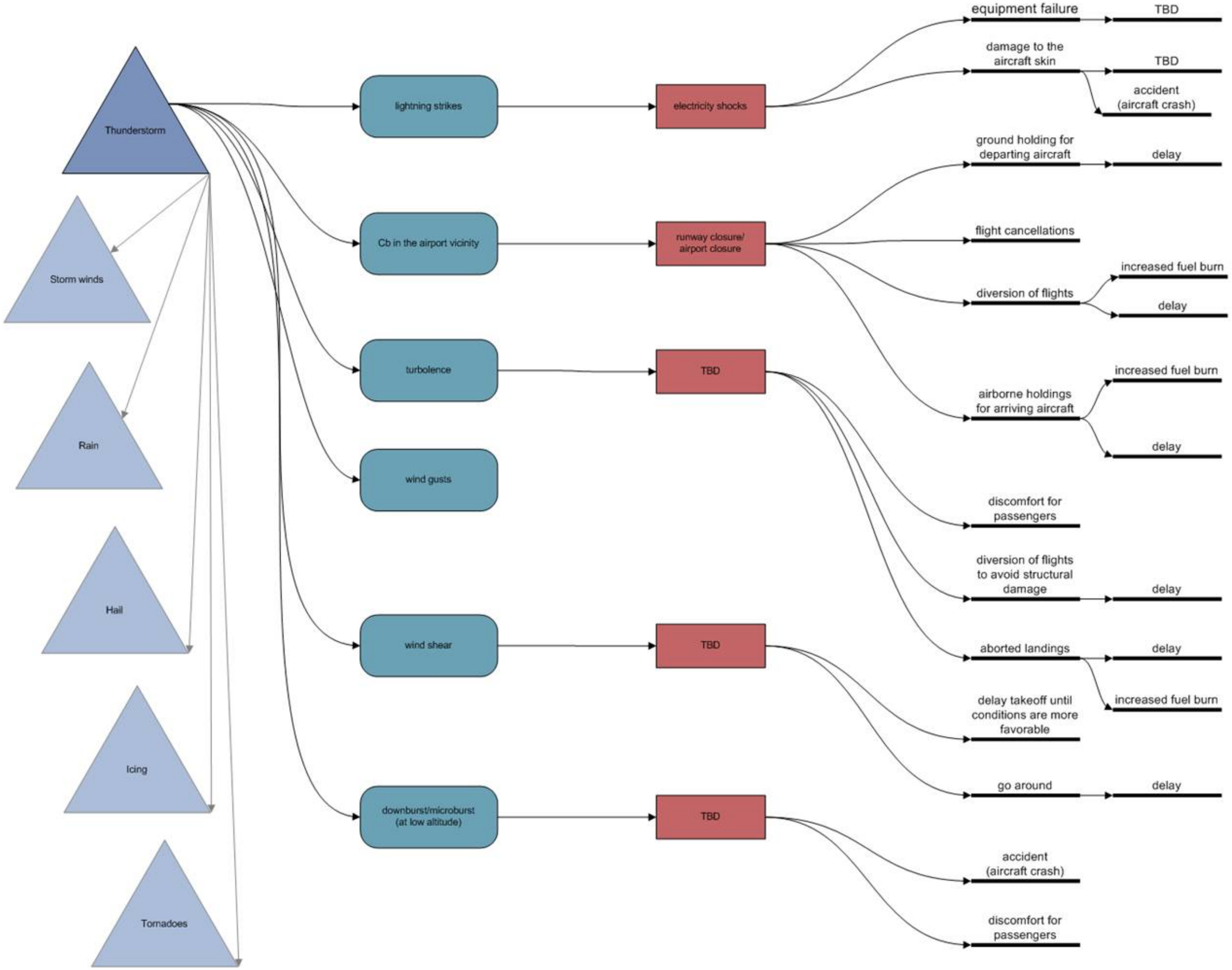

Phenomena
Impacts
Consequences
Winter storm in Scandinavian region
Heavy snow
Hard wind
Icy road
Flooding
Snowy or frozen railway structures
Fallen trees on railway tracks
Snowy or frozen road
Fallen trees on road
Lower friction
Roads and traffic areas under water
Long-distance train services delays
Commuter train services delayed or reduced
Transportation delays
Damages to rail track
Increased traffic accident rate
Dead or injured persons
Increased road maintenance
Transportation delays
Delayed or cancelled bus services
Temporary reduced speed limits on windy road area / closed bridges
Traffic delays

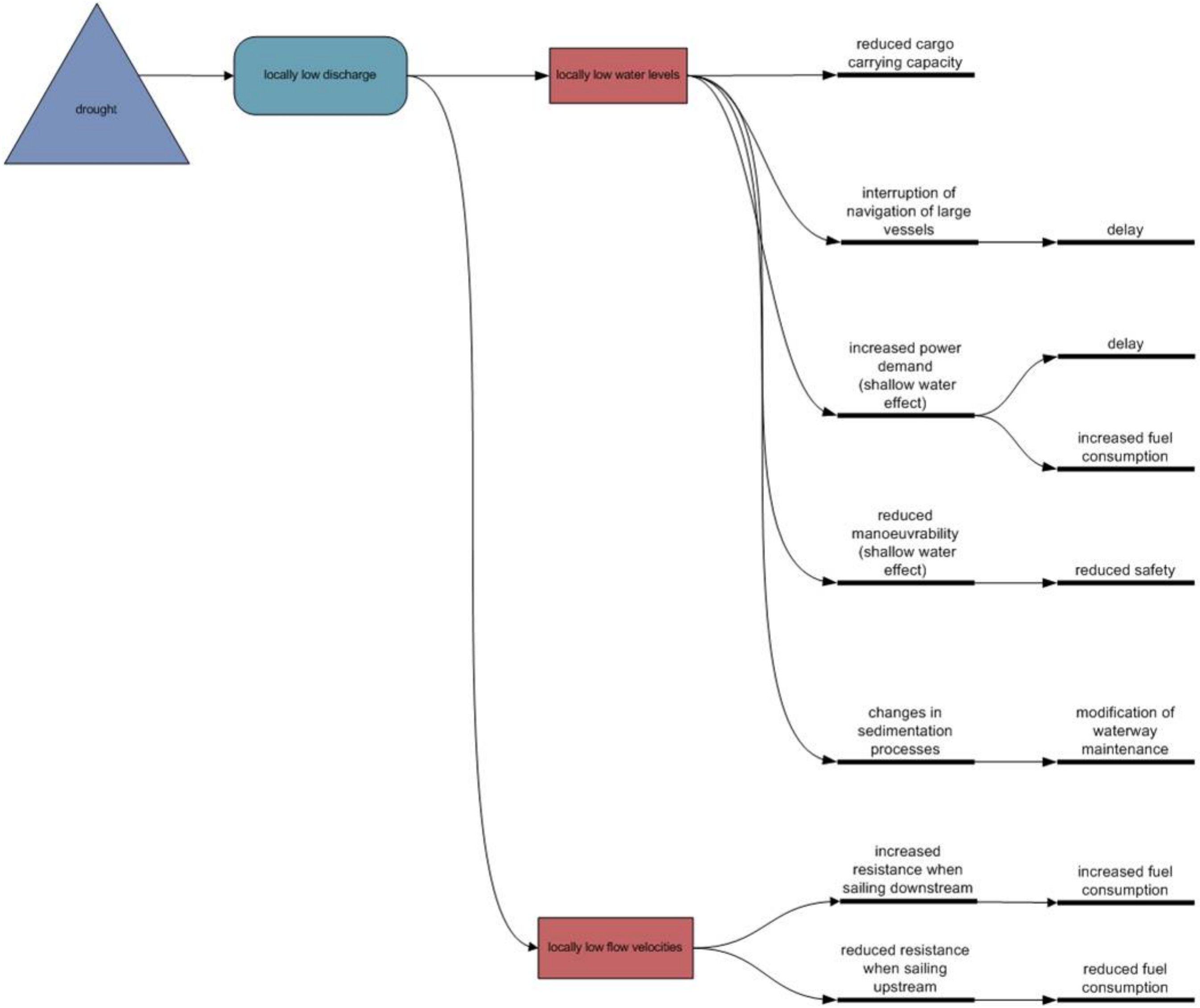

Phenomena
Impacts
Consequences
Heavy rain in North Maritime region (UK)
Flooding
Roads under water, blocked traffic areas
Dam monitoring
Burst river banks
Road traffic stops
Rescue actions (e.g. fire and rescue crews)
Rails under water,
Rail traffic stops
Landslide
Mud flush
Temporary main road closure
Destruction of road infrastructure
Rescue actions (e.g. military forces)
Rail servides disrupted
Strong wind
Falling trees
Injured or dead persons
Road traffic stops

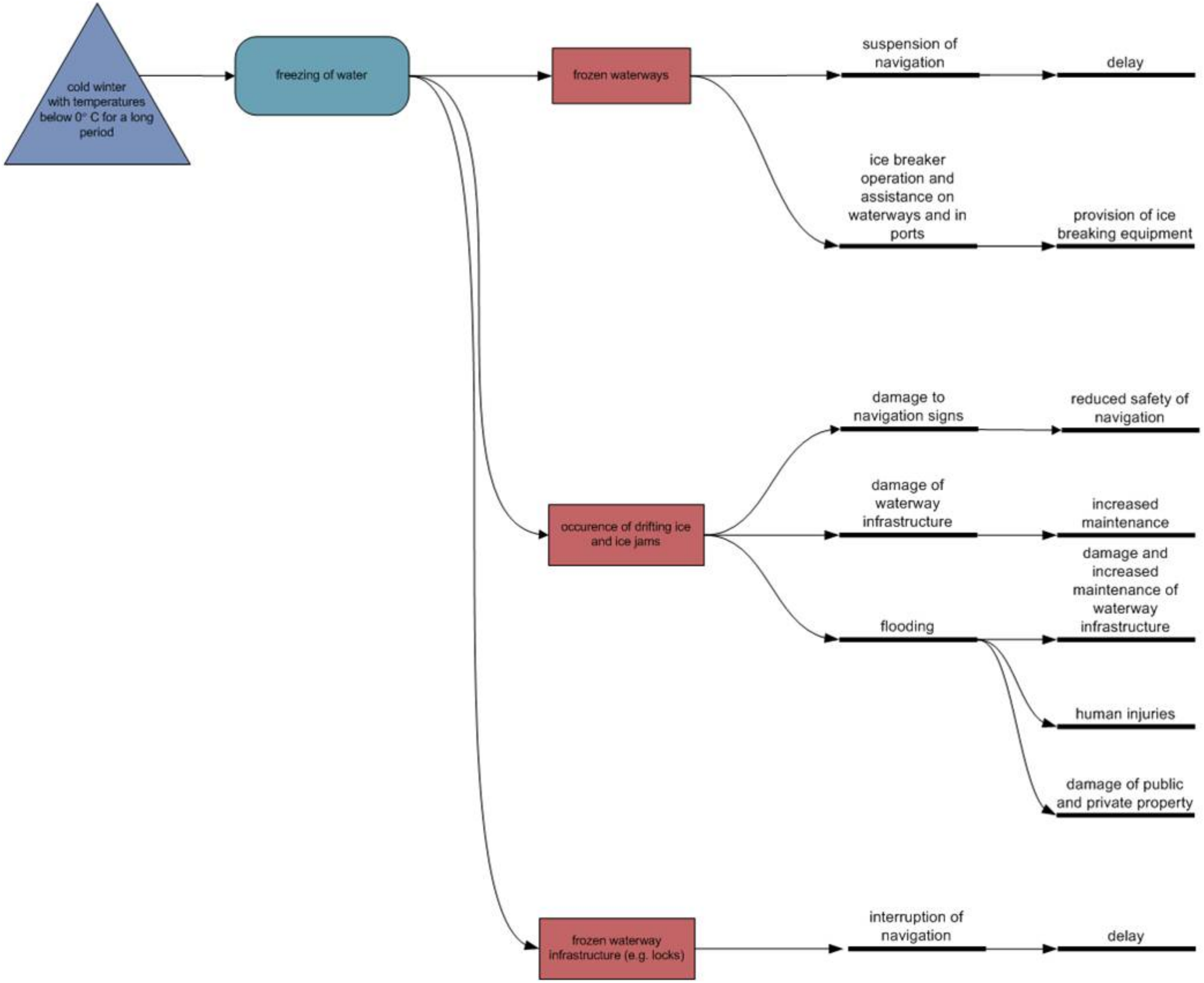

Phenomena
Impacts
Consequences
Heavy rain in the Mediterranean region
Flooding
Rainstorms
Landslides
High seas
River beds burst
Roads under water, blocked traffic areas
Hail storms
Fallen trees
Flash floods, mud flush, closed roads, bridges and traffic areas
Emergency services more difficult to perform
Road transportation stops
Dead or injured persons
Traffic accidents
Damages for vehicles and property
Traffic accidents
Road transportation stops
Closed traffic tunnels
Road transportation stops
Road transportation stops
Railway traffic stops
Destruction of road infrastructure
Structural damages for railway line
Dead or injured persons

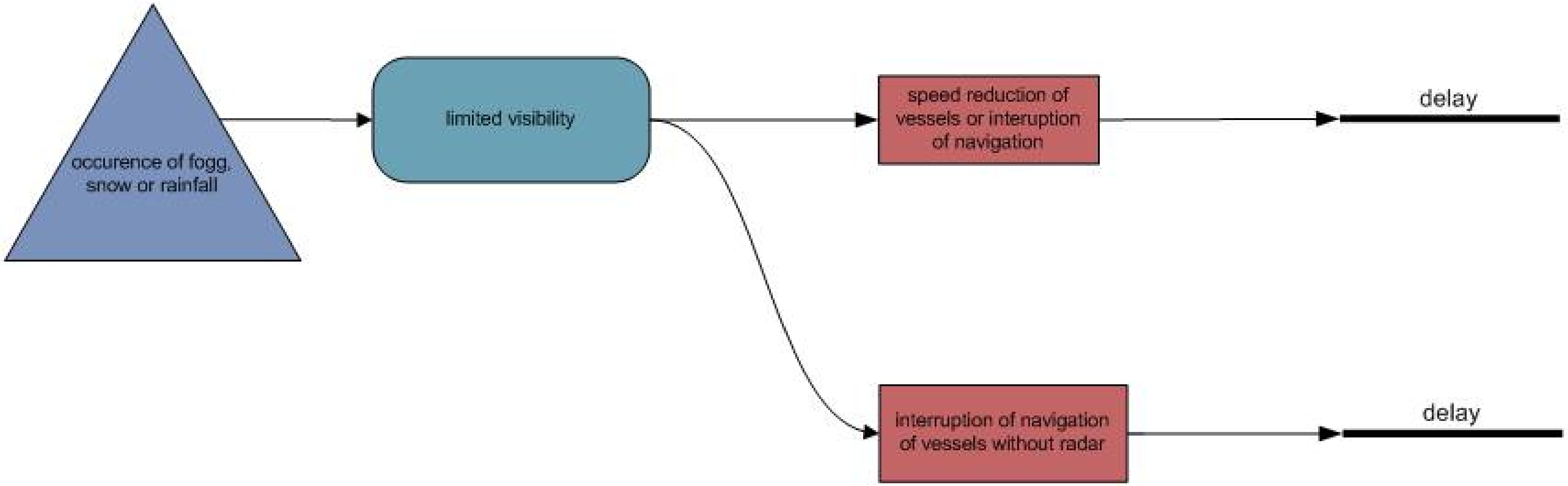

Phenomena
Impacts
Consequences
Heavy rain in the Central Europe
Flooding
Heavy wind
The railway stations and/or rail links under water, rail services stop
The metro stations and/or rail links under water, metro services stop
Roads and traffic areas under water, traffic stops
Trees fall on the rails, rail traffic stops
Trees fall on the roads, traffic stops
Strain on the bus and tram infrastructure
Destruction of road infrastructure
Bridge inspections
Traffic accidents, indirect impacts (e.g. cargo damages)
Injured or dead persons
Car evacuation
Broken sea wall protecting infrastructures
Delays, undesirable effects on traffic interoperability
Traffic accidents
Injured or dead persons

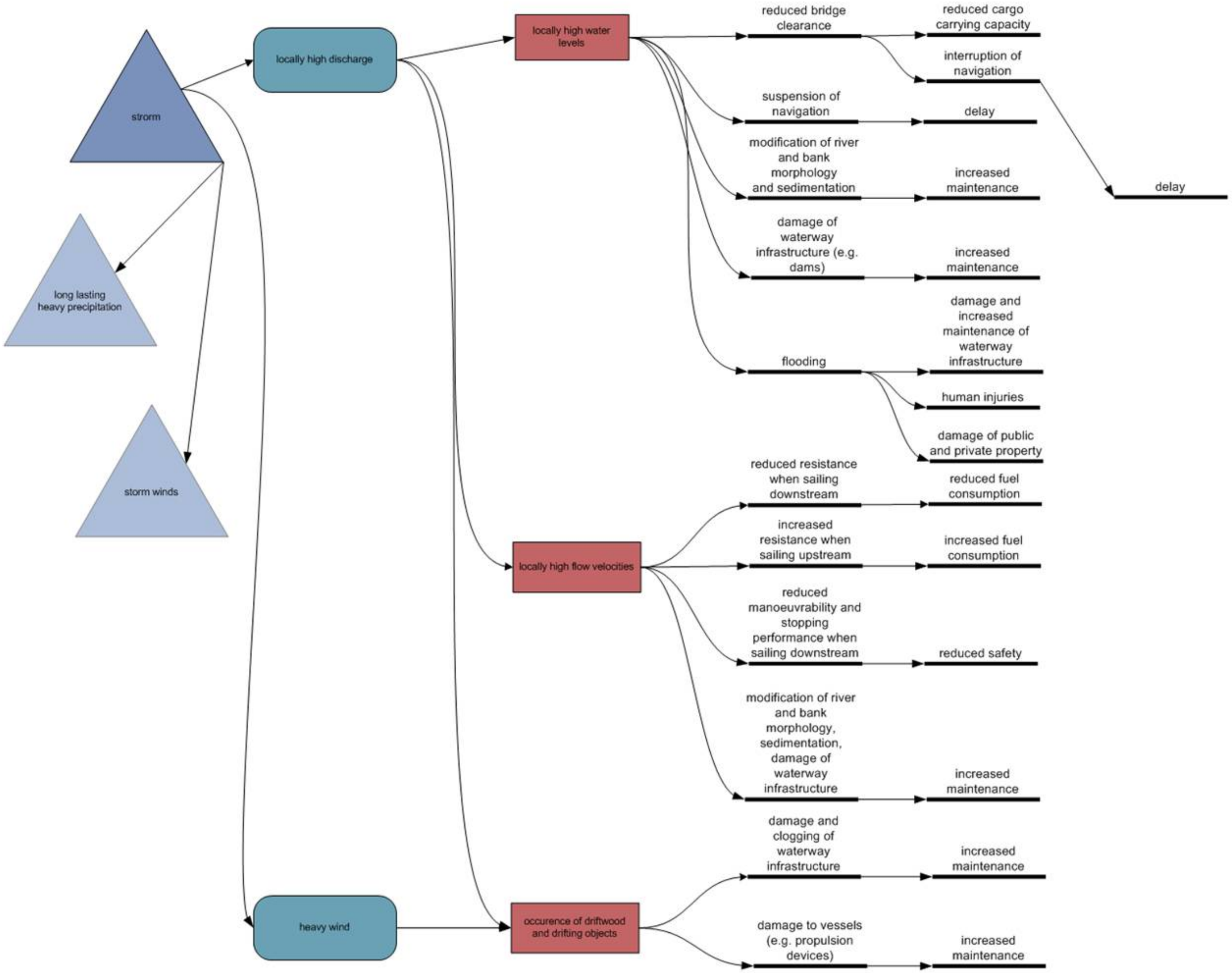

fog
reduced visibility
reduced airport **arrival** capacity due to increased aircraft separation
reduced airport **departure** capacity due to increased aircraft separation
operating restriction for aircraft not equipped with ILS CAT instruments
airport closure/ runway closure
airborne holdings for arriving aircraft
increased fuel burn
delay
ground holding for departing aircraft
delay
diversion of flights
increased fuel burn
delay
airborne holdings for arriving aircraft
delay
increased fuel burn
ground holding for departing aircraft
delay
flight cancellations
delay
diversion of flights
increased fuel burn
delay
flight cancellations
delay
airborne holdings for arriving aircraft
increased fuel burn
delay
ground holding for departing aircraft
delay

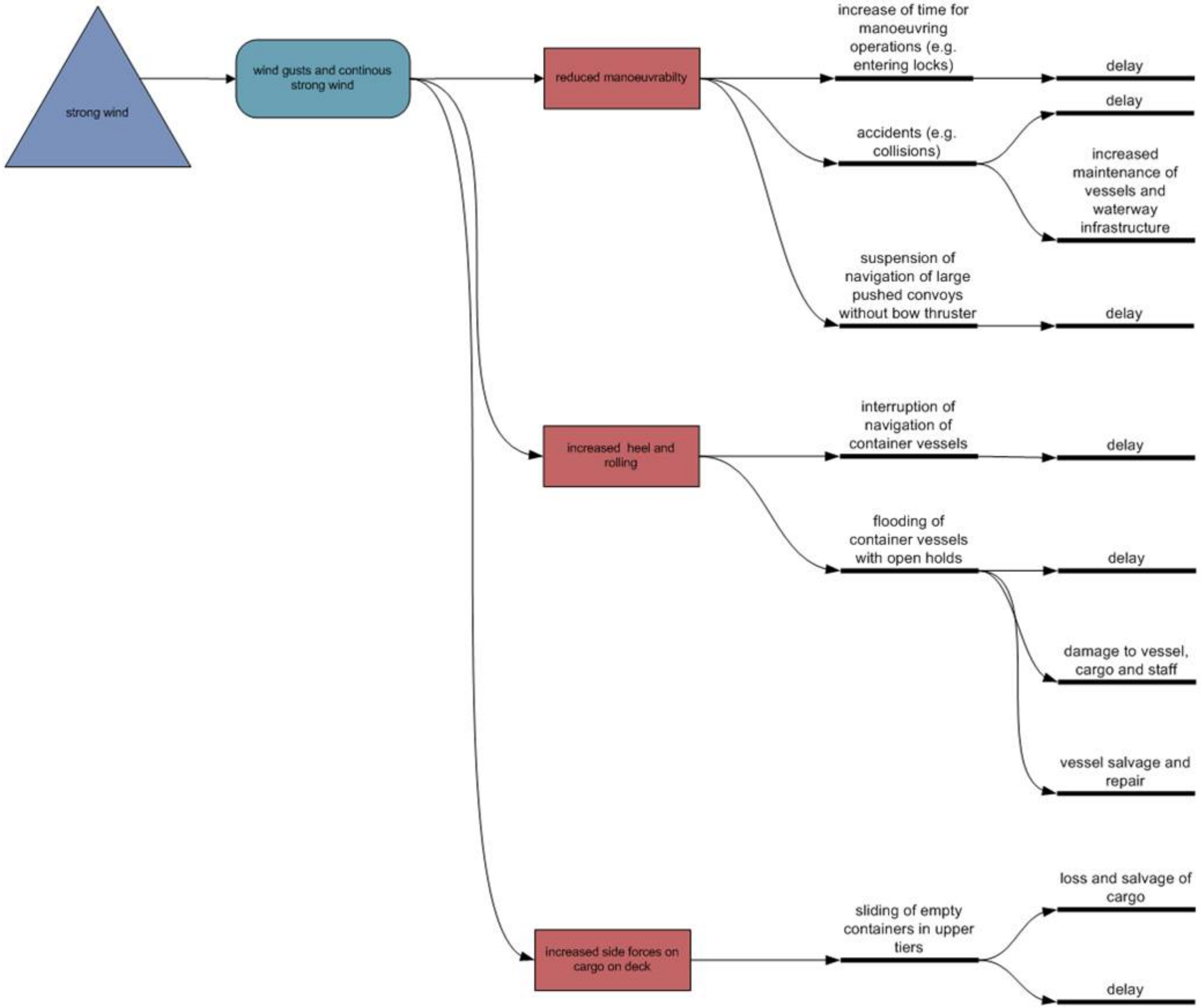

Thunderstorm
Storm winds
Rain
Hail
Icing
Tornadoes
lightning strikes
electricity shocks
equipment failure
TBD
damage to the aircraft skin
TBD
accident (aircraft crash)
Cb in the airport vicinity
runway closure/ airport closure
ground holding for departing aircraft
delay
flight cancellations
diversion of flights
increased fuel burn
delay
airborne holdings for arriving aircraft
increased fuel burn
delay
turbolence
TBD
discomfort for passengers
diversion of flights to avoid structural damage
delay
aborted landings
delay
increased fuel burn
wind gusts
wind shear
TBD
delay takeoff until conditions are more favorable
go around
delay
downburst/microburst (at low altitude)
TBD
accident (aircraft crash)
discomfort for passengers


drought
locally low discharge
locally low water levels
reduced cargo carrying capacity
interruption of navigation of large vessels
delay
increased power demand (shallow water effect)
delay
increased fuel consumption
reduced manoeuvrability (shallow water effect)
reduced safety
changes in sedimentation processes
modification of waterway maintenance
locally low flow velocities
increased resistance when sailing downstream
increased fuel consumption
reduced resistance when sailing upstream
reduced fuel consumption

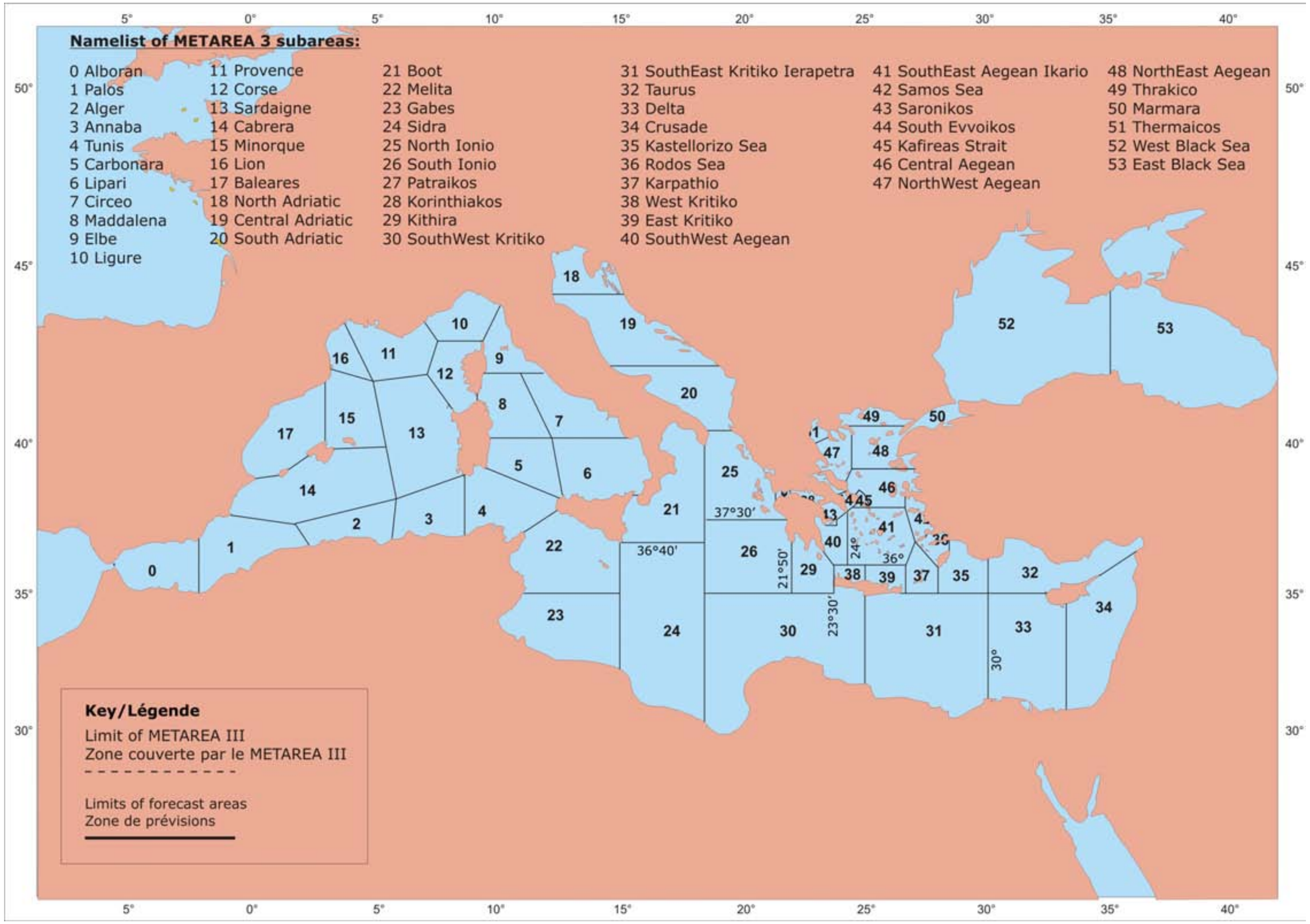

cold winter with temperatures below 0° C for a long period
freezing of water
frozen waterways
suspension of navigation
delay
ice breaker operation and assistance on waterways and in ports
provision of ice breaking equipment
occurence of drifting ice and ice jams
damage to navigation signs
reduced safety of navigation
damage of waterway infrastructure
increased maintenance
flooding
damage and increased maintenance of waterway infrastructure
human injuries
damage of public and private property
frozen waterway infrastructure (e.g. locks)
interruption of navigation
delay


occurence of fogg, snow or rainfall
limited visibility
speed reduction of vessels or interuption of navigation
delay
interruption of navigation of vessels without radar
delay


strorm
long lasting heavy precipitation
storm winds
locally high discharge
heavy wind
locally high water levels
locally high flow velocities
occurence of driftwood and drifting objects
reduced bridge clearance
reduced cargo carrying capacity
interruption of navigation
delay
suspension of navigation
delay
modification of river and bank morphology and sedimentation
increased maintenance
damage of waterway infrastructure (e.g. dams)
increased maintenance
flooding
damage and increased maintenance of waterway infrastructure
human injuries
damage of public and private property
reduced resistance when sailing downstream
reduced fuel consumption
increased resistance when sailing upstream
increased fuel consumption
reduced manoeuvrability and stopping performance when sailing downstream
reduced safety
modification of river and bank morphology, sedimentation, damage of waterway infrastructure
increased maintenance
damage and clogging of waterway infrastructure
increased maintenance
damage to vessels (e.g. propulsion devices)
increased maintenance


strong wind
wind gusts and continous strong wind
reduced manoeuvrabilty
increase of time for manoeuvring operations (e.g. entering locks)
delay
accidents (e.g. collisions)
delay
increased maintenance of vessels and waterway infrastructure
suspension of navigation of large pushed convoys without bow thruster
delay
increased heel and rolling
interruption of navigation of container vessels
delay
flooding of container vessels with open holds
delay
damage to vessel, cargo and staff
vessel salvage and repair
increased side forces on cargo on deck
sliding of empty containers in upper tiers
loss and salvage of cargo
delay

Appendix C: Limits of Mediterranean forecast areas



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ISBN 978-951-38-6326-5 (URL: http://www.vtt.fi/publications/index.jsp)
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