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ORIGINAL PAPER

Severe weather affecting European transport systems: the identification, classification and frequencies of events

**Andrea Vajda · Heikki Tuomenvirta · Ilkka Juga ·
Pertti Nurmi · Pauli Jokinen · Jenni Rauhala**

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Abstract Severe weather can have serious repercussions in the transport sector as a whole by increasing the number of accidents, injuries and other damage, as well as leading to highly increased travel times. This study, a component of the EU FP7 Project EWENT, delineates a Europe-wide climatology of adverse and extreme weather events that can be expected to affect the transport network. We first define and classify the relevant severe weather events by investigating the effects of hazardous conditions on different transportation modes and the infrastructure. Consideration is given to individual phenomena such as snowfall, heavy precipitation, heat waves, cold spells, wind gusts; a combined phenomenon, the blizzard, is also considered. The frequency of severe weather events, together with the changes in their spatial extension and intensity, is analyzed based on the E-OBS dataset (1971–2000) and the ERA-Interim reanalysis dataset (1989–2010). Northern Europe and the Alpine region are the areas most impacted by winter extremes, such as snowfall, cold spells and winter storms, the frequency of heavy snowfall. The frequency of hot days is highest in Southern Europe. Severe winds and blizzards are the most common over the Atlantic and along its shores. Although heavy rainfall may affect the whole continent on an annual basis, extreme precipitation events are relative sparse, affecting particularly the Alps and the Atlantic coastline. A European regionalization covering similar impacts on the transport network is performed.

Keywords Transportation · Impact thresholds · Severe phenomena · Frequency · European regionalization

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A. Vajda (✉) · I. Juga · P. Nurmi · J. Rauhala
Meteorology, Finnish Meteorological Institute, P.O. Box 503, 00101 Helsinki, Finland
e-mail: andrea.vajda@fmi.fi

H. Tuomenvirta · P. Jokinen
Climate Change, Finnish Meteorological Institute, P.O. Box 503, 00101 Helsinki, Finland

1 Introduction

Both weather and climate have an impact on transport systems, affecting safety, the mobility of transportation sectors and the planning, construction and maintenance of the infrastructure (Mills and Andrey 2002). Surface, marine and aviation transportation are all vulnerable, not as much to mean weather conditions as to extremes (Peterson et al. 2008). Extreme weather events can cause significant impacts on the transport sector as a whole by increasing the number of accidents and injuries as well as leading to highly increased travel times and other economic losses. According to the records of reinsurance companies (Munich-Re 2012; Swiss-Re 2012), damages due to meteorological and climate extremes have become more common over the last few decades. Insurance statistics highlight the fact that most of the world's natural catastrophes (nearly 90 % in 2011) are weather-related: in particular, storms (winter storms and tropical cyclones), floods, heat waves and wildfires are responsible for the largest losses (Munich-Re 2012).

Inclement weather, such as heavy snowfall, extreme cold, strong winds, storms, heavy rain, heat waves and fog, contributes to several hazards within the transport sector, the nature and the extent of the impact varying according to the mode of transportation and the resilience of the region in which they occur. The magnitude of the influence and corresponding damage depends not only on the intensity of the weather extreme but also on the preparedness of society for different extreme weather conditions. Although transportation infrastructure and maintenance systems have been designed keeping in mind the typical weather patterns and climate experienced locally (National Research Council US 2008), experience shows that sometimes even a "minor" weather phenomenon can cause delays and increase accident rates.

The effects of winter weather events constitute the greatest proportion of all disruptive phenomena for transportation over most of the European continent. Severe winter storms, heavy snowfall and extreme cold sometimes disrupt several sectors or even the entire transport system, such as the snowstorm over the UK during February 2–9, 2009, over Western Europe in December 2010 or over the whole continent in February 2012, when the usability of many airports and roads was disrupted. Road maintenance and operating costs, although variable from year to year, are considerable; for example, in the USA, nearly 39 % of annual road operating costs can be attributed to winter maintenance (Pisano et al. 2002). In addition, flight cancelations, road and rail closures and speed restrictions due to heavy snowfall and extreme cold lead to economical losses. Safety during winter conditions is also negatively affected. Snow, sleet or ice on road surface decreases road surface friction, increasing slipperiness, resulting in a sharp increase in accident rates (Andreescu and Frost 1998; Norrman et al. 2000; Salli et al. 2008; Andersson 2010). Additionally, blowing snow reduces visibility.

Strong wind gusts can have a negative impact on transportation in any season, as falling trees can block roads and railways, cause electricity cuts (Rauhala and Juga 2010) and disrupt airport operation and navigation, as in the case of the winter storm Gudrun (January 8–9, 2005), which caused disruption of sea, air and land transport and resulted in casualties in countries along the Baltic Sea coast (Carpenter 2005; Haanpää et al. 2005).

Hazardous conditions triggered by heavy precipitation, floods and fog mainly affect transportation modes during the warm season, but to some extent also all the year round. Heavy precipitation and flash floods endanger road safety and contribute significantly to road fatalities and crashes by reducing the friction of the road surface and the visibility conditions. Rain-related accidents account for about 12–17 % of all road accidents on British roads (Edwards 1999) and about 16–20 % of accidents on Australian roads (Rowland et al. 2007). In addition, heavy rain may reduce traffic speeds and the road capacity by 10–17 % (Agarwal et al. 2005). At the same time, precipitation and floods may lead to landslides, structural damage to rail tracks and road infrastructure and weakening of bridges, implying large repair costs.

Extreme heat particularly causes damage to the road and runway infrastructure, resulting in road surface softening and traffic-related rutting, buckling of pavements and flushing or bleeding of asphalt (Mills and Andrey 2002). On railways, high temperatures can lead to rail misalignments and buckling, as well as equipment failure, creating the hazardous preconditions for such accidents as train derailments, with their potential for injuries, fatalities and property damage (Rossetti 2002; Peterson et al. 2008). In addition, the behavior of drivers and train engineers is also affected by heat waves, leading to an increase in their fatigue, increased reaction times and reduced alertness (Rowland et al. 2007).

The frequency and intensity of hazardous weather phenomena and their potential impacts on the transportation network have been changing over the most recent decades. The consequences for transportation of the projected changes in extremes may be both negative and positive. Various indicators already exist to characterize the behavior of extreme events. Several earlier studies have focused on the analysis of indices of climate extremes based on the observational data or reanalysis data (Frich et al. 2002; Klein Tank and Können 2003; Groisman et al. 2005; Alexander et al. 2006; Moberg et al. 2006; Della-Marta et al. 2007, 2009). In a recent study by Smith and Lawson (2011), extreme event climate thresholds for greater Manchester, UK, were defined utilizing meteorological observation series. This was done using a set of objective criteria, based on previously defined indices. The percentiles and other criteria classifying extreme events were set at a stringent level, indicating most probable harmful impacts on society. As a result, critical thresholds for daily maximum temperature, daily snowfall amount and maximum wind gust were 29.2 °C, 6 cm and 60 knots (ca. 30 m/s), respectively. The dates identified by the climate thresholds were compared against the dates of weather-related harmful events extracted from the historical archive search.

Since we want to be able to link the frequencies of events to their physical impacts and further to their consequences for the transport system, we applied a different approach, utilizing so-called impact indices in determining the variation in adverse and extreme events (see Sect. 2).

The objective of our study is to provide a Europe-wide, comprehensive climatology of adverse and extreme weather events that are expected to affect the transport network. First, we define and classify the severe weather events by investigating the effects of hazardous conditions on different transportation modes and infrastructure. We focus on individual phenomena, such as snowfall, heavy precipitation, heat waves, cold spells and wind gusts; we also include a complex phenomenon, the blizzard. Ranking and impact thresholds for these phenomena are defined based on the reviews of the literature and media reports as well as on local studies covering the link between hazardous phenomena and traffic accidents. The frequency of severe phenomena and changes in their spatial extent at the European level are analyzed for the recent climate (1971–2000). Based on the parallel features indicated in the spatial variation in the weather phenomena studied, we also introduce a regionalization of European severe weather phenomena, delimiting the climate regions dominated by similar events harmful for transportation.

2 Defining the selected impact indices

There are various methods available for analyzing adverse and extreme weather events, such as percentile-, absolute-, threshold- and duration-based indices as well as other indices indicating significant societal impacts (Alexander et al. 2006; Stephenson 2008). Since our study aimed at assessing the effects of weather phenomena on a particular target sector, i.e., transportation, we defined a set of quantitative impact threshold indicators based on critical weather parameters, such as daily temperature, precipitation and wind data. A classification defined by three threshold levels was developed for several weather phenomena. Assuming exposure of the transport system to weather phenomena, the qualitative descriptions of the thresholds are the following:

> First threshold: Adverse impacts to the transport system may start to occur especially if the resilience against the phenomena in question is at a low level.
>
> Second threshold: Some adverse impacts are expected. Their severity depends on the resilience of the transport system.
>
> Third threshold: The weather phenomena are so severe that it is very likely that adverse impacts will occur.

The impacts and consequences related to exceeding a particular threshold vary across Europe and depend on the transport mode. It is important to note that the weather events exceeding one or more of the thresholds may occur several times a year and so they are not necessarily extremes occurring with a very low frequency; however, they have potentially harmful effects on operations and the infrastructure. Ideally, continuous response functions between the intensity of weather phenomena and the consequences should be defined. However, the definition of continuous response functions would require a large amount of data consisting of meteorological information and consequences (number of crashes, information about delays and costs, etc.) in various locations throughout Europe.

The impact threshold definition process started with a literature survey on the subject, covering more than 150 research papers published in national and international journals and books, as well as reports of research projects and research councils (Leviäkangas et al. 2011; Juga and Vajda 2012). Although our own focus was mainly on European situation, most of the publications are concerned with extreme weather impacts reported from Canada, the USA and Australia. Each weather phenomenon was considered separately, including the described disruptive level and thresholds for it, the reported impacts and/or consequences on different transportation modes (road, rail transportation, aviation, inland navigation), and the country/city where the weather event had occurred. The phenomena considered were the windstorm (wind gusts), snowfall, flash floods/rainfall, extreme temperatures (coldness and heat waves), freezing rain and ice deposits and also their combinations, e.g., the blizzard, consisting of simultaneous wind gusts, low temperature and snowfall. In addition, a large number of hazardous weather events and their impacts on transportation were identified and investigated, based mainly on media reports. The database of media reports includes more than 190 cases of different weather events and their impacts on society from January 1, 2000 until September 10, 2010, e.g., the Gudrun windstorm in Northern Europe in January 2005 and the Western European snow storm from the beginning of February 2009.

Finally, the warning practices of the European Weather Services were also taken into account when estimating the impact thresholds. Warning thresholds differ somewhat from one country to another, but many Weather Services have a tripartite “warning palette,” based on the severity of the impacts of the hazardous weather elements. The warnings from most of the European National Weather centers are gathered into a common database for use at the Meteoalarm Web site (www.meteoalarm.eu).

The three threshold values mentioned above were defined for different weather parameters, derived from daily data series, based on the severity of the identified impacts and consequences. The values (at least the lowest threshold) should occur in most parts of Europe, so that the areal probability distribution in the present climate could be assessed. The 24-h time-frame is due to data limitations: the temporal resolution of the data used in the calculations is daily. Furthermore, the time interval of the regional climate analyses used in the assessment of changes in severe weather phenomena in the future climate, analyzed in the additional studies (Vajda et al. 2011), is also daily.

Our study is a component of the EU FP7 Project EWENT that has the objective of assessing the impact of extreme weather on the European transport system. The approach taken involved identifying causal linkages between weather phenomena, their impacts and consequences for the transport system. The EWENT project focused on the following consequences: accidents with casualties or injuries, infrastructure collapse or damage, and time delays (Leviäkangas and Saarikivi 2012). The character and severity of consequences from weather phenomena depend not only on the weather phenomena themselves but also on exposure and vulnerability of the transport system (e.g., IPCC 2012). Exposure and vulnerability of the transport system are influenced by a wide range of factors such as transport policy, socioeconomic and technical development. Separating meteorological and non-meteorological factors enables further analysis of different factors affecting risks and their comparisons across Europe as well as identifying measures and options for mitigating risks to the transport sector. For example, percentile-based thresholds contain built-in assumptions related to exposure and vulnerability of transport systems to extreme weather.

3 Data description

The frequency and probability of adverse weather conditions over the European continent were derived from two gridded datasets: the E-OBS dataset version 3.0 (Haylock et al. 2008), produced through spatial interpolation of daily station data, and the reanalysis ERA-Interim dataset, produced at the European Centre for Medium-range Weather Forecasting (ECMWF); the latter dataset is produced by a multi-source data assimilation system and describes the state of the atmosphere, as well as the land and ocean wave conditions (Uppala et al. 2005; Dee et al. 2011).

The E-OBS European high-resolution land-only gridded dataset of daily surface temperature and precipitation has been developed within the EU-funded ENSEMBLES project. The daily mean (TG), maximum (TX), minimum (TN) temperature and precipitation sums were derived through interpolation of the ECA&D (European Climate Assessment and Data) station data described by Klok and Klein Tank (2009). The full period of records used for the interpolation is 1950–2009, but the period 1961–1990 has the highest station density (Hofstra et al. 2009). The E-OBS dataset has been derived through a three-stage process using the kriging interpolation method. E-OBS data with a 0.25° regular latitude–longitude grid were used to derive the adverse and extreme weather indices over the European continent for the 30-year period (1971–2000) as follows: the 2-m daily mean temperature for cold spells, the maximum temperature for heat waves and the total daily precipitation for heavy rainfall. Since the dataset does not distinguish between the liquid and solid states of precipitation, we have calculated the frequency of snowfall using the daily precipitation amounts precipitated at a daily mean temperature below 0 °C. Since the interpolation methodology has smoothed the magnitudes of the extremes in the variation in the variables, we have applied rough corrections: a factor of 0.66 for precipitation and an anomaly of -1.1 °C for maximum temperature data as indicated by the cross-validation with station observations (Haylock et al. 2008).

The data used in the computation of wind gusts and blizzards originate from the ERA-Interim datasets (1989 to the present day). ERA-Interim (Simmons et al. 2006) uses 4D variational analysis on a spectral grid with a triangular truncation of 255 waves (corresponding to approximately 80 km) and a hybrid vertical coordinate system with 60 levels; it produces four analyses per day (00, 06, 12 and 18 UTC) and two 10-day forecasts per day, initialized from analyses at 00 and 12 UTC. The wind gust parametrization implemented in ERA-Interim incorporates friction, horizontal wind speed and its estimated standard deviation at the 10-m level as well as universal turbulence spectra to finally calculate the 3-s wind gust values (ECMWF 2007). Although the reanalysis dataset does not cover the baseline period (1971–2000) applied in our study, its enhanced data assimilation system and the improved spatial resolution justified the use of this dataset. Thus, the time-frame used in the wind gust and blizzard analysis covered the 22-year period from 1989 to 2010 (available at the time of the study). The frequency of wind gusts was derived from the 6-h forecast of 10-m wind gusts, while a blizzard was computed using the 6-h forecast wind gust and precipitation sum together with the 6-h reanalyzed mean temperature.

The outer edges of the domain covered by the two datasets in the present study are as follows: 32°N, 25°W and 72°N, 45°E for the E-OBS data, and 30.937°N, 26.018°W and 73.124°N, 45.7°E for the ERA-Interim reanalysis data. The spatial distribution of the probability and frequency of adverse events in terms of exceeding selected thresholds over Europe in the period studied is presented using maps.

4 Results

4.1 Impact thresholds indicators for the weather phenomena studied

The impact thresholds for the various different weather phenomena were defined based on the risk for their adverse impacts on transportation. The risk varies with geographical location within Europe; for example, a snowfall of 1–2 cm may increase road traffic accidents and jams in the Mediterranean countries, but is most probably a minor problem in the Nordic countries. However, if the road surface were already icy, then even a light snowfall might be dangerous; especially for pedestrians and cyclists (Penttinen et al. 1999; Anttila 2001). This emphasizes the role of efficient road maintenance actions.

A weather phenomenon may have different impacts on different transport means; for example, the above-mentioned snowfall of 1–2 cm is less harmful for rail traffic. However, if it is accompanied by low temperatures and strong winds, it may impact rail transportation: drifting snow in cold conditions may result in the rail points getting stuck. Hence, combinations of different weather parameters often have more disruptive impacts compared to that of a single weather phenomenon. For this reason, besides the indicators for single phenomena, impact thresholds for complex phenomena, such as a blizzard (a combination of heavy snowfall, strong wind gusts and low temperature), were also defined.

Table 1 shows the defined impact thresholds for snowfall (R_s), cold spells (T_{mean}), heat waves (T_{max}), heavy rainfall (R), wind gusts (WG) and the blizzard. Three threshold values were defined for a single phenomenon based on the impacts and consequences reported in the literature review and media survey.

As mentioned above, light snowfall may cause local slipperiness and thus increase the traffic accident risk, especially if the road surface temperature is below 0 °C and anti-icing has not been carried out. Thus, the first threshold was defined as $\geq$ 1 cm/24 h. The second

Table 1 The impact thresholds for different weather phenomena

Phenomena	Thresholds		
	1st	2nd	3rd
Snowfall	$R_s \geq 1$ cm/24 h	$R_s \geq 10$ cm/24 h	$R_s \geq 20$ cm/24 h
Cold spell	$T_{\text{mean}} \leq 0$ °C	$T_{\text{mean}} \leq -7$ °C	$T_{\text{mean}} \leq -20$ °C
Heat wave	$T_{\max} \geq 25$ °C	$T_{\max} \geq 32$ °C	$T_{\max} \geq 43$ °C
Heavy rainfall	$R \geq 30$ mm/24 h	$R \geq 100$ mm/24 h	$R \geq 150$ mm/24 h
Wind gust	$WG \geq 17$ m/s	$WG \geq 25$ m/s	$WG \geq 32$ m/s
Blizzard	$R_s \geq 10$ cm/24 h, $T_{\text{mean}} \leq 0$ °C, $WG \geq 17$ m/s		

R_s snowfall, T_{mean} daily mean temperature, $T_{\max}$ daily maximum temperature, R rainfall, *WG* 3-s wind gust

threshold, $R_s \geq 10$ cm/24 h, is connected to a moderate risk of adverse impacts on different transport means. According to earlier case studies in Finland, the rate of car accidents may be doubled compared to the daily mean accident rate of the whole winter in the case of 10-cm snowfall (Juga 2012). Similarly, on February 1–2, 2009, in the UK, many business activities, schools and transportation systems had to be closed due to a snowfall of this magnitude, resulting in substantial monetary costs (Grumm 2009). When the snowfall exceeds 20 cm/24 h (the third threshold), it most probably has a substantial disruptive impact on transportation, causing closure of roads (such as in Eastern Sweden on December 17, 2009) or cancelation of flights and closure of airports (for example, in Central Europe, during the winter of 2009–2010 and again in December 2010).

Regarding low temperature (a cold spell), the first threshold, $T_{\text{mean}} \leq 0$ °C, represents the limit, when the risk of slippery conditions on roads and airfields increases due to changes in the state of precipitation from rain to snow or sleet and wet surfaces begin to freeze. The reason for using the daily mean temperature in the criterion instead of the daily minimum temperature is that the daily mean temperature is more explicitly linked to the form of precipitation than the daily minimum temperature, because it describes the mean conditions during the 24-h period. Daily minimum temperature may describe the conditions only for a short period during the night, and it has more local variation due to topography and total cloudiness, although the above criterion can also lead in some exceptional cases to false interpretation of the form of precipitation, for example, when, after a very cold morning, the temperature is rising due to warm advection and precipitation occurs mostly later during the day. In this situation, although the daily mean temperature may be slightly below zero, the state of precipitation may be liquid. However, in a large data sample, the criterion applied is probably valid in most of the cases. Apparently, there is a wide ranging difference for rain snow threshold temperature, but as a general agreement in most of the studies, $T_{\text{mean}} = 0$ °C roughly marks the transition that defines snow to mixed-phase precipitation (Gillies et al. 2012). The threshold of −7 °C constitutes the mean temperature value below which the usage of salt loses its effectiveness, requiring the application of more salt or more expensive de-icing chemicals. On the other hand, cold conditions may cause failures in railway traffic as rail points may get stuck by drifting snow at low temperatures. Inland waterway transport can also be disrupted by the starting of ice formation on rivers. Extreme cold, $T_{\text{mean}} \leq -20$ °C, results in various disturbances: public transport services may encounter interruption due to fuel problems (for example, in Norway during winter 2009–2010), ice formation on rivers and coastal sea areas badly disrupts waterway transport, and railway traffic can encounter bad problems due to ice and snow accumulation underneath railway carriages, as happened in Finland during the winters of 2009–2010 and 2010–2011.

Strong wind gusts may be connected with either intensive large-scale low-pressure systems or mesoscale convective systems (thunderstorms), the latter mainly in the summertime. Typical impacts of strong wind gusts are power cuts and blocked roads and railway lines, due to fallen trees. Local damage can already occur at wind gusts of 17 m/s (the first threshold), while gusts of 25 m/s or more typically cause widespread damage. Wind gusts of over 32 m/s result in substantial damage, such as very large number of fallen trees, widespread and long-lasting power failures and reduced visibility and high waves at sea. A validation of the highest threshold occurred in connection with the storm that hit Southern Finland after the passage of a low-pressure system on December 26, 2011. The strongest measured wind gust was 31.5 m/s (Juga and Vajda 2012), resulting in many fallen trees and long-lasting power failures. As a consequence of the storm, several roads and railway lines were blocked, badly disrupting traffic. Mesoscale Convective Systems (MCSs) and the related violent wind gusts can cause wide area damage. The most widespread and long-lived of these convective windstorms are termed “derechos.” Walker and Mote (2005) investigated derechos in the USA. During the occurrence of a derecho, the wind gusts exceed 26 m/s and the affected damage area has a major axis length of at least 400 km. When examining derecho fatalities, it appeared that vehicular and boating deaths accounted for nearly 50 % of all fatalities. Vehicular fatalities typically occurred in one of three ways: (1) overturned tractor semi-trailer, (2) felled tree landing on a car and (3) a vehicle driven into a felled tree. Marine fatalities typically occurred as drownings when either sailing vessels or motorized boats were overturned due to violent winds. Derechos can occur also in Europe, sometimes even in the northern part, e.g., in Finland on July 5, 2002, when 1 million m^3 of trees felled due to a violent MCS (Punkka et al. 2006).

When strong wind gusts are combined with low temperature and snowfall, we are dealing with a high-impact weather phenomenon, the blizzard (impact thresholds: $R_s \geq 10$ cm/24 h, $T_{mean} \leq 0$ °C, WG ≥ 17 m/s (Table 1)). Blizzards can cause considerable disturbances to railway and road traffic and aviation, resulting in delays and cancelations or interruption of operations. During a blizzard in Finland in November 2008, the traffic accident rate rose fourfold compared to the average daily accident rate during winter (Rauhala and Juga 2010).

Similarly, large precipitation amounts and high temperatures may cause relevant, negative consequences to the European transport systems. Table 2 contains a summary of typical impacts and possible consequences on transport sector related to the impact thresholds for the selected weather parameters. It is based on the literature review and media survey reported in Leviäkangas et al. (2011), which contains more impacts and consequences with reference to reported cases.

4.2 Climatology of the selected adverse phenomena

4.2.1 Wind gust

The European wind gust climatology for the three different thresholds is presented in Fig. 1. Clearly the most gust-prone areas are over or adjacent to large sea and ocean areas, whereas the more eastern parts of Europe experience fewer severe wind gusts. The lowest threshold wind gusts (17 m/s) are fairly common throughout Europe, with average frequencies of between 1 and 40 days per year over mainland Europe. Extreme wind gusts ($\geq$ 25 m/s), on the other hand, do not occur frequently; only the coastal areas adjacent to

Table 2 Typical impacts and possible consequences on transport systems related to the impact thresholds for the selected weather phenomena

Parameter, threshold	Typical impacts	Possible consequences
$R_s \geq 1$ cm/24 h	Local road slipperiness	Increased road accident rate
$R_s \geq 10$ cm/24 h	Reduced friction; road slipperiness; rail points get stuck; repeated clearing of the runways	Increased road accident rate; delays and cancelations in road and rail traffic as well as in aviation
$R_s \geq 20$ cm/24 h	Reduced friction; slippery roads and airfield pavements; accumulated snow banks; poor visibility	Disturbed traffic; high road accident rate; closed roads; airfields temporarily closed, plenty of delays; and cancelations of trains
WG $\geq$ 17 m/s	Some windfall trees; reduced maneuverability	Local problems in road and rail traffic; suspension of small boat operation
WG $\geq$ 25 m/s	Windfall trees; reduced maneuverability; reduced visibility due to the blowing snow or dust	Electricity cuts; delays and cancelations in air, rail and road traffic; ferry traffic is disturbed
WG $\geq$ 32 m/s	Large amount of fallen trees; damages to traffic control devices; damages to structures; reduced visibility; high waves	Ferries stay at the harbor; airfields closed; material damages; delays and cancelations in rail and road traffic; wide and long-lasting power failures
$T_{\text{mean}} \leq 0$ °C	Slipperiness; ice formation; snowfall, freezing rain/drizzle/fog	Increased road accident rate; premature deterioration of road and runway pavements due to freeze–thaw cycles
$T_{\text{mean}} \leq -7$ °C	The effect of road deicing salt reduced; snow structure suitable for drifting; ice formation on rivers	Increased road accident rate; delays and cancelations in road and rail traffic; inland waterway transport may be disrupted
$T_{\text{mean}} \leq -20$ °C	Strong ice formation on rivers; freezing of devices and fuel; dangerous exposure to cold	Delays and cancelations in inland waterway transport and rail traffic; limitations for the personnel working outdoors; fuel problems
$R \geq 30$ mm/24 h	Water on streets and roads; reduced friction	Increased road accident rate
$R \geq 100$ mm/24 h	Flooded underpasses and lower lying streets; reduced friction; poor visibility	Increased road accident rate; delays in road traffic; damages to (secondary) roads, especially culverts; increased maintenance and repair for road and rail structures
$R \geq 150$ mm/24 h	Flooded underpasses and lower lying streets; inundation; reduced friction; poor visibility; landslides	Increased road accident rate; delays in road traffic; damages to roads; increased maintenance and repair for road and rail structures
$T_{\max} \geq 25$ °C	Fatigue among drivers	Somewhat increased road accident rate
$T_{\max} \geq 32$ °C	Fatigue among drivers; high road surface temperatures	Increased road accident rate; softening and traffic-related rutting of pavement; roadway buckling
$T_{\max} \geq 43$ °C	Dangerous heat stress; high road surface; and rail temperatures	Increased road accident rate; damage to pavement; roadway and rail track buckling
Blizzard $R_s \geq 10$ cm/24 h WG $\geq$ 17 m/s $T_{\text{mean}} \leq 0$ °C	Fallen trees, snow banks, slippery roads and runways, poor visibility, rail points may get stuck	Increased road accident rate; delays and cancelations in all transportation modes

Table gives examples for more impacts and consequences with reference to reported cases see Leviäkangas et al. (2011). For abbreviations see Table 1

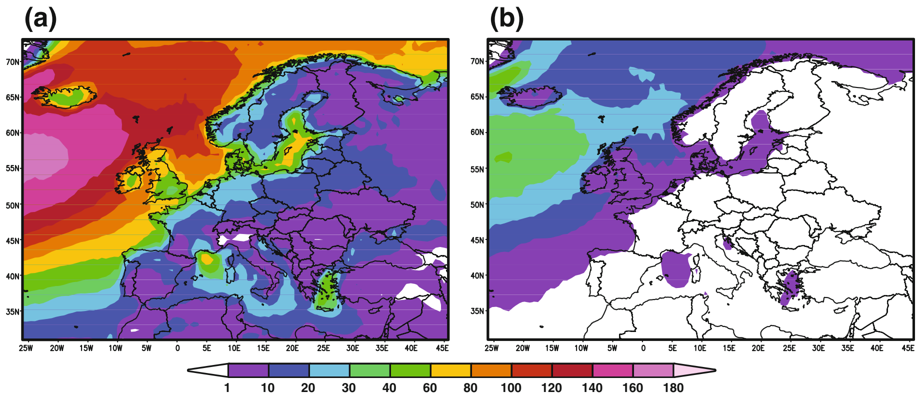


Fig. 1 Average number of days per year with a wind gust exceeding **a** 17 m/s and **b** 25 m/s during the period 1989–2010 based on ERA-Interim data

the North Atlantic Ocean and the Mediterranean Sea are affected by such wind speeds, with a maximum frequency of 10 cases per year. According to ERA-Interim data, hurricane-force wind gusts (≥ 32 m/s) do not appear to be an annual threat for the European continent. However, it must be noted that the results are based on the gridded wind gust data, derived from the reanalyzed model results, not directly from observations. There are several factors that can affect the quality of the wind gust data in ERA-Interim, e.g., the handling of convectively driven wind gusts, the small-scale topography/weather-induced wind gusts and the model physics and resolution. The wind gust climatology shown in this paper should therefore be treated only as a rough estimate. The results portray the large-scale spatial variability fairly well, but the gusts caused by smaller temporal and/or spatial scale phenomena can at least locally increase the frequencies of strong wind gusts beyond what the ERA-Interim data indicate. An example of underestimation of summertime wind gust speeds is presented in Vajda et al. (2011).

4.2.2 *Snowfall*

Snow events (≥ 1 cm/24 h) occasionally impact the entire continent (Fig. 2a). The frequency of snowfall increases toward Eastern and Northern Europe and in the Alpine region to a 20–25 % frequency (100–140 days/year). Adverse snowfalls (≥ 10 cm/24 h) occur on average between 1 and 5 days per year over Western, Southern and most of Central Europe, and 5–20 days in Scandinavia (Fig. 2b). The most affected regions are the Alps, the Scandinavian mountains and Iceland, experiencing between 45 and 55 days with ≥ 10 cm snowfall per year and 5–25 cases with ≥ 20 cm snowfall (Fig. 2c). Nevertheless, snowfall events of the latter magnitude have also occurred sporadically in other regions of Scandinavia, Eastern Europe and the Balkan Peninsula, altogether 30–40 cases during 1971–2000.

4.2.3 *Cold spells*

According to the spatial distribution of adverse low temperatures (Fig. 3), the frequency of frost days ranges between 100 and 200 over Scandinavia and northward of 50°N over Russia, with the highest values in the Scandinavian mountains and Iceland (220–220 days/

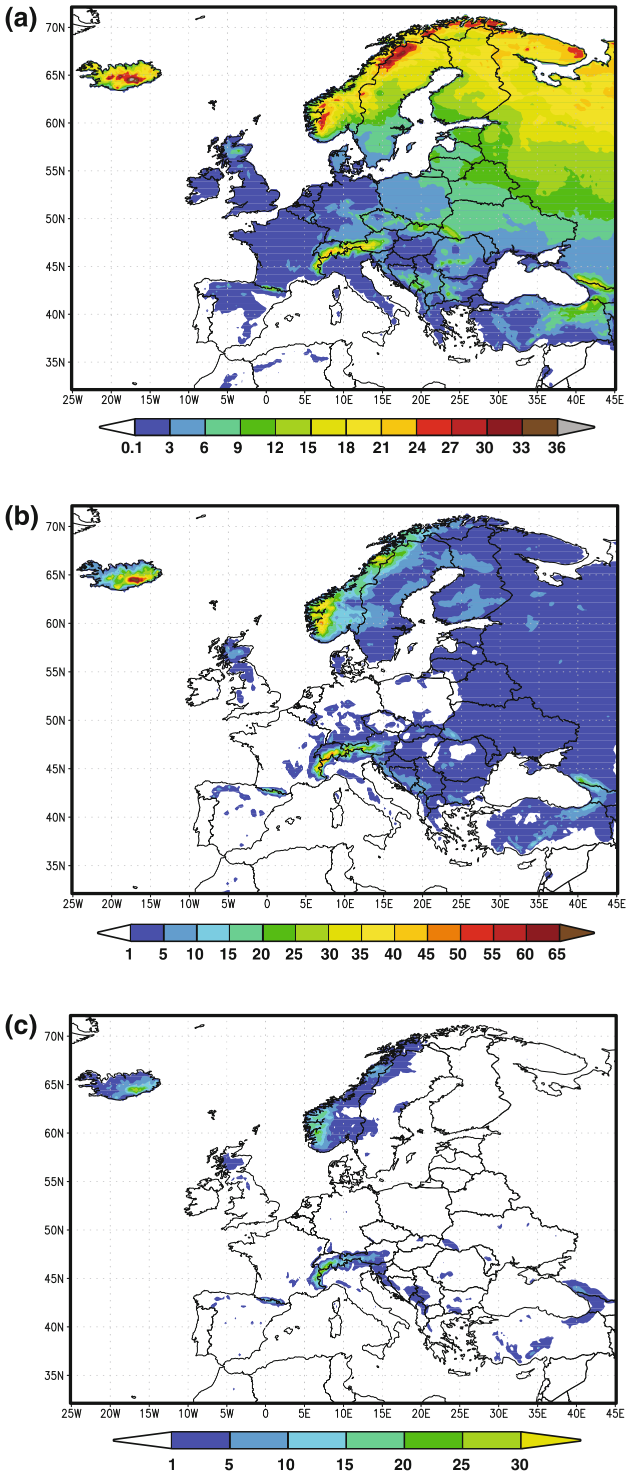
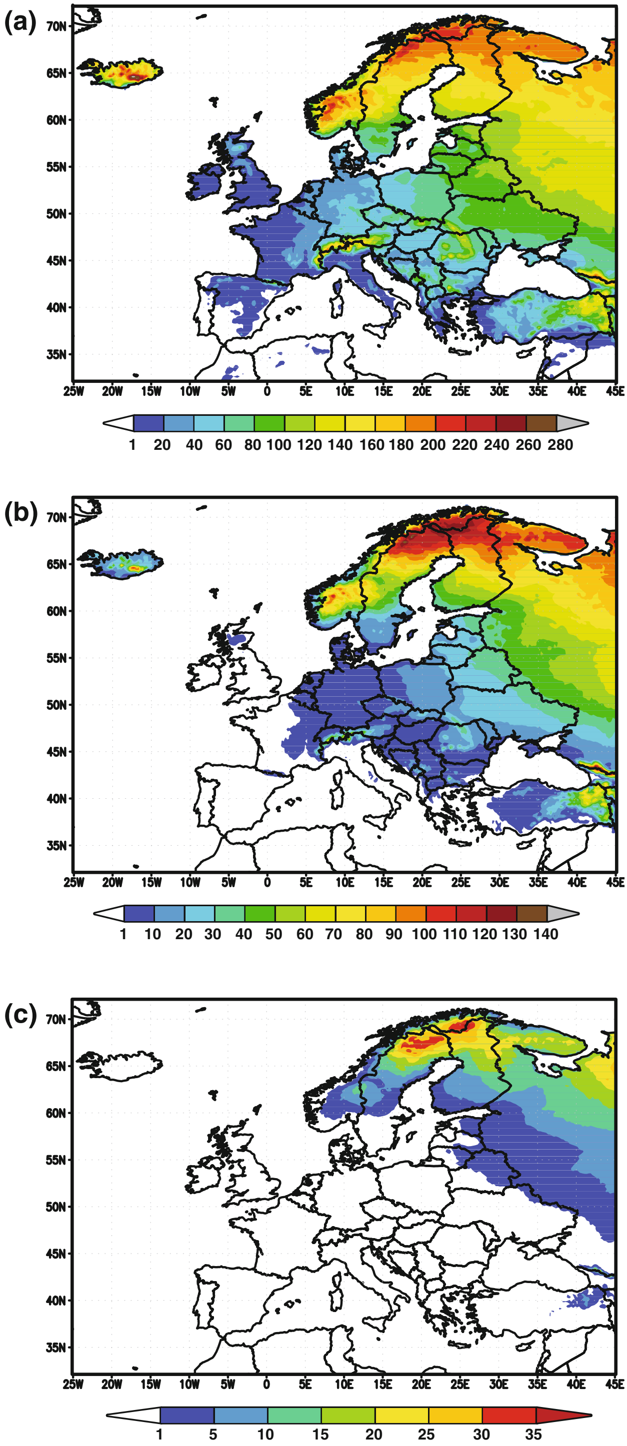


Fig. 2 **a** Frequency (in percent) of days with snowfall exceeding 1 cm and average number of days per year with snowfall exceeding, **b** 10 cm and **c** 20 cm during the period 1971–2000 based on the E-OBS data

Fig. 3 Average number of days per year with daily mean temperature below: **a** 0 °C, **b** −7 °C and **c** −20 °C, during the period 1971–2000 based on the E-OBS data



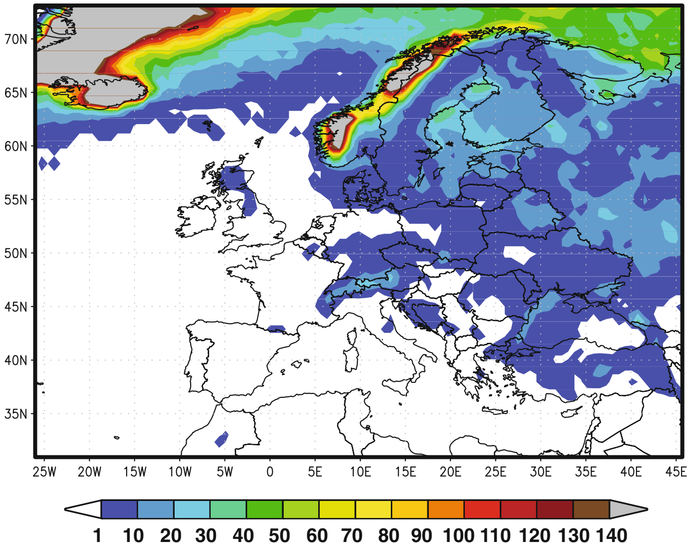


Fig. 4 Total number of blizzard events during the period 1989–2010 based on the ERA-Interim data

year). In general, frost days affect the rest of the continent on 1–60 days/year (Fig. 3a). Adverse cold, with a temperature ≤ -7 °C, occurs in 1–20 cases/year over the central and western part of the continent and in 100–110 cases/year in northern Scandinavia (Fig. 3b). Most of the continent is free of very extreme cold spells (< -20 °C), except Scandinavia and the northeastern part of Europe (5–30 days/year).

4.2.4 Blizzards

Blizzard conditions are mostly confined to the northern and eastern parts of Europe (Fig. 4), where strong wind gusts, heavy snowfall and low temperatures are most likely to occur simultaneously. The emphasis on Eastern Europe is due to the lower temperatures and higher probability of heavy snowfall, whereas the western parts of the continent usually lack these aspects more often. In low-lying areas, the highest number of blizzard events during the 22 years of data was around 30, i.e., on average once or twice a year. The Scandinavian mountains and Iceland, however, experience more such events than the rest of Europe by an order of magnitude.

The same shortcomings apply to the blizzard climatology as to the wind gust climatology. The coarse resolution of ERA-Interim cannot reveal the strong wind gusts or heavy snowfall caused by small-scale weather phenomena or complexities of topography. For this reason, it must be recognized that the number of blizzard events may be substantially higher in mountainous regions. Nevertheless, the climatology map does show the spatial pattern of blizzards in Europe over the low-lying areas and also the corresponding frequency estimates based on favorable large-scale conditions.

4.2.5 Heat waves

As is to be expected, there is a significant meridional decrease in the frequency of high temperatures ($\geq$ 25 °C) from 35 to 45 % on the Iberian Peninsula to a maximum of 5 % in

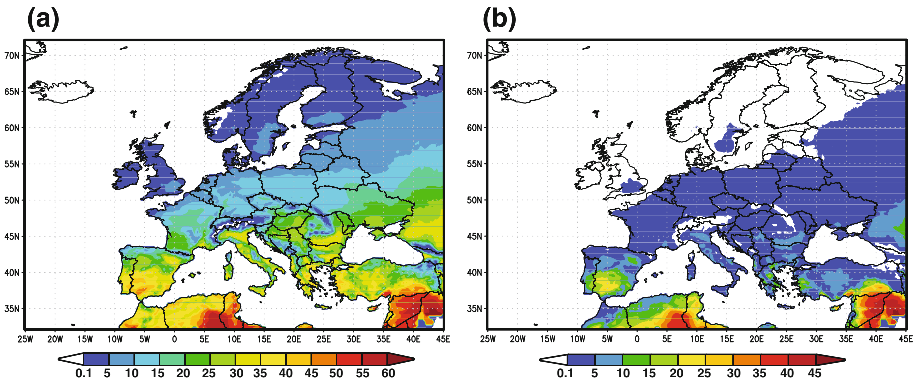


Fig. 5 Frequency of daily maximum temperature exceeding **a** 25 °C and **b** 32 °C (in percent) during the period 1971–2000 based on the E-OBS data

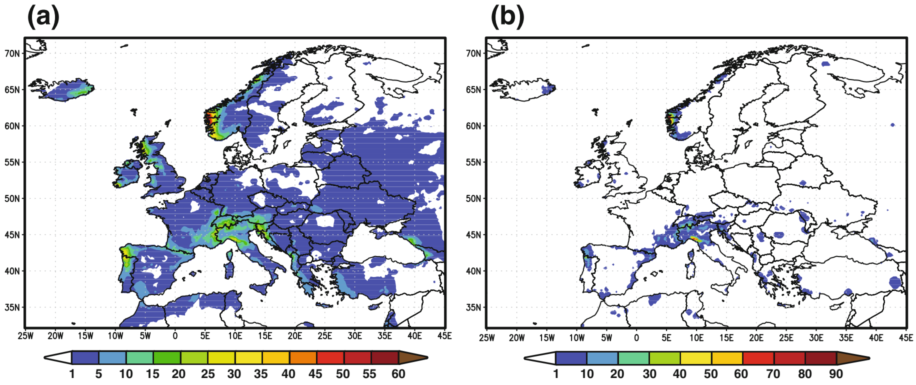


Fig. 6 Spatial variation in daily heavy rainfall expressed as **a** average number of days per year with rainfall exceeding 30 mm (in percent) and **b** total numbers of days with rainfall exceeding 100 mm during the period 1971–2000 based on the E-OBS data

Scandinavia (Fig. 5a). The frequency of hot days ($\geq$ 32 °C) ranges from between 15 and 25 % (40–80 days/year) in southern Europe to 1–5 % (10–20 days/year) in the central and eastern part of the continent (Fig. 5b). Very hot days, with daily maximum temperatures above 43 °C, are very rare, with a maximum of 25 days over the Iberian and Balkan Peninsulas. However, it is worth noting that the high temperature values recorded at individual stations are masked out due to the gridding procedure applied in the E-OBS dataset; the probability of very hot days is thus partly underestimated.

4.2.6 Heavy rainfall

The maps of the spatial variation in strong rainfall intensities (Fig. 6) reveal that most of Europe experiences 1–5 days/year with more than 30 mm rainfall (2 % frequency), except regions in northern latitudes (Fig. 6a). The frequency of adverse rainfall is highest on the western coast of Scandinavia (up to 60 days/year) and in the British Isles, the Iberian Peninsula and the Alps, 20–30 days/year. Very heavy rainfall events ($\geq$ 100 mm/day) are rare, in general 10–20 cases occurring in 30 years over the coastline of Norway and the

Alps and sporadically over the Mediterranean and Eastern Europe (Fig. 6b). In practically, all European countries there are stations that have occasionally measured precipitation amounts exceeding 150 mm per day, but these measurements may not always be part of the E-OBS data archive. Nevertheless, daily precipitation amounts of > 150 mm are very rare; these very high values are therefore mostly leveled out in the E-OBS-gridded data.

5 Discussion and conclusions

The weather phenomena having implications for the transportation sector were defined and ranked. As regards disruptions in surface, air and water transportation, experience shows that the magnitude of harmful weather events does not necessarily have to be extreme, with a very small (1 %) frequency and highly elevated impact level. Phenomena exceeding a lower critical level but having a higher frequency, occurring even several times per season, may result in significant damage, causing delays, compromising the safety of traffic and increasing maintenance costs. Although a set of key indices for climate extremes based on the daily temperature and precipitation data and representing a wide variety of climate aspects already exists, the application of these indicators in transport-focused analyses seemed to be less than adequate. Thus, the newly derived impact indices relate variables to observed impacts and damage in the various different transport modes. Linking weather phenomena and their impact according to defined threshold indices with the different transport systems, these indicators allow the estimation of risks for the consequences of extremes to various transport services and the infrastructure. In addition, threshold indicators provide valuable information to public safety authorities, transport system stakeholders and operation and transport service providers, allowing the management of risks and the improvement of the cost efficiency and reliability of transport services and as well as the planning of resilient transport systems. Besides national level, European-level information on relevant weather-related risks to the transport systems has been compiled (Tuomenvirta and Leviäkangas 2012).

Regarding the climatology of severe phenomena, the European transport system has to cope with a large variety of extreme weather occurring with different probabilities and intensity across Europe. However, based on the frequency analyses of the adverse weather phenomena listed in Table 1, regions showing a similar behavior of severe phenomena can be delimited (Fig. 7), thus providing a beneficial platform for risk assessment for the European transport system: (1) the Northern European (subarctic) region dominated by snowfall and cold spells; (2) the Maritime (oceanic) region—severe winds and floods; (3) the Mediterranean region—heat waves; (4) the Alpine (mountainous) region—snowfall, severe winds and heavy precipitation; (5) the Temperate Central; and (6) Temperate Eastern European regions, characterized by the sporadic occurrence of several types of severe weather rather than any particular weather phenomena. Table 3 lists the characteristics of adverse weather that are common within the regions. Molarius et al. (2012) have used this regionalization in risk assessment of weather hazards and vulnerabilities in the European transport.

We did not perform a detailed trend analysis of the selected severe weather parameters. However, a number of earlier studies on observed changes in extreme temperatures have found decline in cold extremes and increase in warm extremes during the past 50 years or so in Europe (Frich et al. 2002; Klein Tank and Können 2003; Alexander et al. 2006; Moberg et al. 2006; Della-Marta et al. 2007). As for summer temperatures, a significant positive trend has been found for hot days and heat waves over Western Europe since 1880 with the largest trend over the Iberian Peninsula and in central Western Europe (Della-

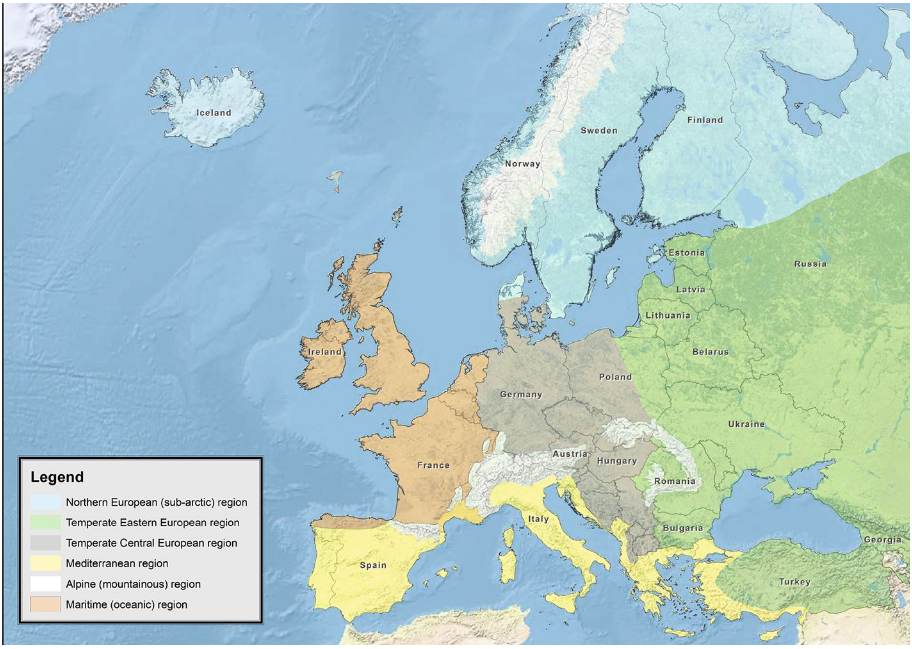


Fig. 7 Classification of severe climate regions based on the changes in spatial variation in phenomena affecting transportation

Marta et al. 2007) associated with an increase in the duration of heat waves. Some of the studies (Klein Tank and Können 2003; Moberg et al. 2006) reported an asymmetric warming, especially for the last decades of the century, with the warm tail warming faster than the cold tail. A significant increase in the number of heavy precipitation days has also been reported in earlier studies (Alexander et al. 2006; Groisman et al. 2005; Klein Tank and Können 2003) for the second part of the twentieth century. Concerning the extreme winds, Della-Marta et al. (2009) and Brönnimann et al. (2012) have found an increasing frequency in more extreme wind strengths over the North Atlantic storm track region. However, there are to our knowledge no studies that have attempted to estimate the impacts of these extreme weather trends to European transportation.

In this study, we assessed quantitative information on the variation in severe weather phenomena on the European scale using available state-of-the-art high-resolution gridded data and reanalysis data. The results of the frequency analysis and a comparison of the dataset with individual local observations of weather events (Vajda et al. 2011) highlighted the shortcomings of the relatively coarse temporal and spatial resolution of the data and its reliability for certain parameters. It is likely that even with the corrections applied to the maximum temperature and precipitation data, the magnitudes of the extremes are smoothed compared to station observations. Similarly, certain features of the wind gust data from reanalysis are not always consistent with the observations. The results portray the large-scale spatial variability fairly well, but the gusts caused by smaller temporal and/or spatial scale phenomena can at least locally increase the frequencies of the strong wind gusts beyond what the ERA-Interim data indicate. A more accurate estimation of wind gusts could be produced by downscaling coarse resolution reanalysis datasets to gain more insight into the frequency of small-scale effects and topography-induced processes.

Table 3 Characterizations of climate regions based on the analysis of spatial variation in extreme weather affecting transportation (see Fig. 7)

Region	Typical/characteristic phenomena/features
Northern European region	Dominated by impacts of extreme winter weather phenomena. The frequency of cold spells, heavy snowfalls and blizzards is the highest in this European geographical zone. For example, 20–35 days/year with $T_{\mathrm{mean}} \leq -20$ °C in Lapland; 40–50 days/year with $R_{\mathrm{s}} \geq 10$ cm/24 h on the western coast of Norway and Iceland as well as blizzards locally over 140 cases during 1989–2010; extreme winds especially over Iceland; heavy rainfalls are frequent over the fjord coast and westerly exposed mountain ranges of Norway. Conversely, the frequency of hot spells is the lowest within the Northern European zone and level of preparedness is low
Maritime (oceanic) region	Features relatively moderate frequency of extreme winter phenomena: less than 10 days/year with $T_{\mathrm{mean}} \leq -7$ °C; only few days with −20 °C or heavy snowfall. Due to the low frequency of extreme winter events, most of the affected countries have a reduced level of preparedness for winter phenomena. The frequency of high temperatures is higher over the continental Europe (5 % for $T_{\max} \geq 32$ °C), while heavy rainfall and high wind gusts are more common over the British Isles (80 cases/year with WG $\geq$ 17 m/s)
Mediterranean region	Region is affected particularly by summer extreme phenomena, characterized by the highest frequency of heat waves in Europe (locally, 25 % frequency of $T_{\max} \geq 32$ °C) and areas with sporadically very heavy rainfall ($R \geq 100$ mm/24 h). Although frost days and snowfalls may occur on an annual basis, extreme winter events are uncharacteristic. Dust events also impact the region occasionally, especially in the southeastern Mediterranean
Alpine (mountainous) region	Covers not only the Alps but also the Carpathians, the Pyrenees and in many aspects also the Scandinavian Mountains. These regions, due their topography, can have remarkably different extreme phenomena compared to their surroundings. Characteristic extreme phenomena affecting the Alpine zone are cold spells (on average 50–60 days $T_{\mathrm{mean}} \leq -7$ °C), heavy snowfall (ca. 20 days $R_{\mathrm{s}} \geq 20$ cm/24 h), blizzards (ca. 20 cases in Alps during 1989–2010) and heavy rainfall (about 20 cases/year $R \geq 100$ mm/24 h). The frequency and intensity of these phenomena is somewhat moderated in the Pyrenees by its southern location and lower elevation
Temperate Central European region	Region is less affected by very extreme weather events. However, adverse weather events might impact the area on yearly basis. There is a 5 % frequency of $T_{\max} \geq 32$ °C, 2 % of $R \geq 30$ mm/24 h and on average 15–20 days/year with WG $\geq$ 17 m/s. Winters occasionally bring blizzards and sporadically $R_{\mathrm{s}} \geq 10$ cm/24 h (ca. 5 events/year), especially over the southern part of this region, together with up to 20 days $T_{\mathrm{mean}} \leq -7$ °C
Temperate Eastern European region	This region differs from the Central European one by the more pronounced effect of continentality. Accordingly, cold spells are more frequent and intense during winter, 30 days/year with $T_{\mathrm{mean}} \leq -7$ °C in the western part of the zone, increasing eastward to 70–80 days/year. Very extreme cold spells ($T_{\mathrm{mean}} \leq -20$ °C) are frequent over the eastern part. Blizzards and heavy snowfall events ($R_{\mathrm{s}} \geq 10$ cm/24 h) impact the Eastern European zone ca. 5 times/year. Frequency of days with $T_{\max} \geq 32$ °C is 5 % annually, being more frequent over the southern part of the region ($\sim$10 %). The spatial variation in heavy rainfalls does not differ from the general European patterns, although very heavy events ($\geq$ 100 mm/24 h) may locally occur

The impacts and consequences of strong wind, heavy snowfall and rainfall, extreme heat and cold and blizzards on the transportation network have been widely and thoroughly studied. The large differences in the probabilities and intensities of these phenomena across the European area need to be considered in transport policy and traffic operation. Also, under the projected climate change, weather and climate extremes are likely to continue to occur in the future, their potential effect on the transport system being possibly both negative and positive. This implies large challenges for risk management and climate change adaptation, including the need for innovation with regard to old practices. In extension of our results given here, we proceed further with the assessment of changes in the probability and intensity of severe weather events relevant to transportation in the future climate (Vajda et al. 2011).

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