Observed and future changes of extreme winter events in Europe with implication for road transportation

Andrea Vajda[1], Heikki Tuomenvirta[1] and Pauli Jokinen[1]

Finnish Meteorological Institute
Helsinki, Finland

Corresponding author's E-mail: andrea.vajda@fmi.fi

ABSTRACT

Extreme weather events can have remarkable impact on the transport sector, causing severe damages and large economic losses. The mobility and safety of road transport is mostly affected by extreme winter conditions that might lead to significant disruptions, increased accident risk and costs of damage. Extremes are likely to continue to occur in the future due to the projected climate change; consequences of changes may be both negative and positive for all the transportation sectors.

This study provides an overview of changes in the extreme and adverse winter phenomena that are most likely to affect the European road network focusing on present climate and the projected future climate (1970-2070). Individual phenomena, such as heavy snowfall, freezing temperatures, strong wind gusts and also their combination, blizzard is considered. The estimation of the recent and past events is based on the observed data available from the E-OBS dataset and the ECMWF ERA-Interim re-analysis dataset. The analysis of the relevant hazardous weather phenomena takes into account the ranking and impact threshold values defined from the viewpoint of the infrastructure and different transport modes such as road, rail, aviation and waterways. Future changes in the probability of severe events are assessed based on six high-resolution regional climate model simulations produced in the ENSEMBLES project. A range of statistical methods are applied to define the features of the extremes such as their probability, changes in the spatial extension, intensity and temporal duration.

Keywords: adverse winter phenomena, climate change, European road transportation

1 INTRODUCTION

Weather and climate impact surface transportation, affecting the safety, mobility of transportation sectors and the planning and maintenance of the infrastructure. According to the statistics there is an increase in damages caused by the consequences of adverse and extreme weather events on transport system. The mobility and safety of road transport is mostly affected by extreme winter conditions, such as heavy snowfall, ice, freezing rain, blizzard and strong winds that might lead to significant disruptions, increased accident risk and costs of damage.

Earlier studies show that the highest accident risk and disruption in road transportation is associated with snowfall events and rain or sleet on freezing road surface, resulting in decreased road surface friction, increased slipperiness and reduced visibility. Studying the effects of rain, snow and temperature on traffic accidents in Quebec, Canada Andreescu and Frost [3] pointed out that the rate of accidents increases sharply on snowy days; another special hazard was the freezing rain. Low temperatures were instead rather modifier of accident conditions than a root cause. Studies of winter road conditions in Sweden showed that the highest accident rates were associated with rain or sleet fallen on frozen road surface in the southern part (Andersson [2], Norrman et al. [11]), while northward the hoarfrost was the dominant cause of road slipperiness (Andersson [2]). In Finland, the accident risk resulting in damages or injuries was about four times higher during snowy and icy road surface compared to dry conditions (Salli et al. [13] as referred in Juga et al. [7]). According to Kulmala and Rämä [9] about 25% of all fatal accidents occurred on icy and snowy road conditions.

Extreme winter weather conditions do not endanger the transportation only across Northern Europe; snowfall and blizzard phenomena may cause traffic chaos and disruption over most of the European continent, e.g. the snow storm from February 2-9, 2009 over UK, December 2010 over Western Europe or February 2012 over the whole continent. On the other hand, the preparedness of countries and of drivers to severe winter conditions also varies across Europe. Besides snow conditions, formation of ice on roads is of major focus even in the countries with less severe winter weather. This phenomenon becomes a significant problem for maintenance especially on marginal nights, when temperatures are close to freezing (Chapman and Andersson [5]).
Weather and climate extremes are likely to continue to occur in the future due to the projected climate change; consequences of changes may be both negative and positive for transportation. As cold extremes are projected to decrease, road networks would benefit of milder winter conditions with less snowfall in some regions, while Northern Europe would experience an increase in the frequency of the near 0 °C, resulting in more slippery conditions. At the same time transportation infrastructure was designed for typical weather patterns and environmental conditions, thus changes in extremes will impact also the infrastructure structure.
This paper provides an overview of changes in the extreme and adverse winter weather events that are most likely to affect the European transport system, with special consideration for road network, focusing on the observed present climate (1970-2000) and the projected future climate (2040-2070). Individual phenomena, such as heavy snowfall, freezing temperatures, strong wind gusts and also their combination, blizzard is considered.
The study is associated with the EU/FP7 project EWENT. The major goal of the project is to study the impacts of hazardous weather on the European transportation system by taking into account the changing climate.

2 METHODS AND DATA

2.1 Threshold values for critical winter conditions

The analysis of the relevant adverse and extreme weather phenomena takes into account the ranking and impact threshold values defined from the viewpoint of different transport modes, such as road, rail, aviation, waterways, and infrastructure (Leviäkangas et al. [10]). Threshold values were defined based on the literature and impact reviews as well as reviews of hazardous cases. Indices were expressed as the number of days on which a variable falls above or below a fixed threshold. Three impact threshold indices were chosen for each of the following phenomena (Table 1) in such a way that the values can occur in most parts of Europe in the present climate: snow, cold spell and wind gust. The threshold index for blizzard was defined using the combination of snowfall, wind gust and low temperature indices.

	SNOW	COLD SPELL	WIND GUST	BLIZZARD
1st threshold	≥ 1 cm/24 h	≤ 0 °C	≥ 17 m/s	Rs ≥ 10 cm/24 h T ≤ 0 °C Wg ≥ 17 m/s
2nd threshold	≥ 10 cm/24 h	≤ -7 °C	≥ 25 m/s	
3rd threshold	≥ 20 cm/24 h	≤ -20 °C	≥ 32m/s	

Table 1. The defined threshold indices for the studied winter phenomena.

2.2 Gridded observational data

The estimation of the recent and past (1971-2000) adverse weather conditions over the European continent is based on two gridded datasets: the E-OBS dataset (Haylock et al. [6]) 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 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 mean (TG), maximum (TX), minimum (TN) temperature and precipitation were derived through interpolation of the ECA&D (European Climate Assessment and Data) station data described by Klok and Klein Tank [8]. E-OBS data with a 0.25° regular latitude-longitude grid was used to derive the adverse and extreme weather indices over the European continent. Since the interpolation methodology has smoothed the magnitudes of extremes in the variation of variables, we have applied correction factors for precipitation (0.66) and maximum temperature data (-1.1 °C) indicated by the cross-validation with station observations (Haylock et al. [6]).
The ERA-Interim datasets cover the period from 1989 to present day. Although the reanalyses dataset does not cover the entire period (1971-2000) applied in our study, its enhanced data assimilation system and the improved spatial resolution justified the use of this dataset. ERA-Interim (Simmons et al. [14]) uses 4D-variational analysis on a spectral grid with triangular truncation of 255 waves (corresponds 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.
In the evaluation of probabilities and frequencies of adverse weather phenomena we utilized the parameters from the two datasets as follows: 2-m daily mean temperature values (cold spell calculation), 2-m daily mean

temperature (T ≤ 0 °C) and total daily precipitation from E-OBS dataset (snowfall calculation); 6-hour forecast of 10 m wind gust (wind gust calculation), 6-hour forecast of 10 m wind gust and precipitation sum, 6-hour reanalysed 2-m mean temperature from ERA-Interim dataset (blizzard).
The outer edge of the domain covered by the two datasets in the present study are: 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 reanalyses data.

2.3 Scenario data

In order to assess the changes in the probability and frequency of adverse or extreme weather conditions in Europe in the future climate we used six high-resolution (ca. 25x25 km^2) Regional Climate Model (RCM) simulations produced in the ENSEMBLES project. All the applied GCM runs used A1B (medium, non-mitigation) emission scenario. The RCMs were selected in such a way that those provide all variables required for our analyses and covered the time horizon studied (2041 to 2070). The regional climate change projections chosen were: SMHIRCA-ECHAM5-r3, SMHIRCA-BCM, SMHIRCA-HadCM3Q3, KNMI-RACMO2-ECHAM5-r3, MPI-M-REMO-ECHAM5-r3, C4IRCA3-HadCM3Q16.
Daily values of 2–m mean temperature, maximum temperature, total precipitation and wind gust were used in the computation of changes in probability of severe weather phenomena. Even though regional climate models are run at high resolution, the evaluation of many extremes may be complicated, since gridded data provided by RCMs is more homogeneous in space than observations, thus attenuating extremes (Rummukainen [12]). Internal variability is a natural characteristic of the climate system. GCMs do simulate natural variability but, for climate change experiments this is considered to be noise that obscures the signal due to external forcings. The use of three different GCMs reduces the noise due to internal variability in the multimodel mean scenarios presented in this study.
Based on the calculation of frequencies using the six RCMs, the multi-model mean of the change compared to the control period (1971-2000 and 1989-2009 for wind gusts and blizzards), furthermore the upper and lower limits of the change has been defined and presented for each threshold of the adverse and extreme phenomena. The multi-model mean is the average change indicated by the six models giving each model equal weight. The range of changes is also indicated for each grid that describes well the inter-model variability, i.e. upper and lower limit. The upper limit (maximum) shows the “most positive” change of any model, while the lower limit (minimum) indicates the “most negative” change.

3 RESULTS

3.1 Snow

As aforementioned, snow represents the greatest challenge for transport system operations. Heavy snowfall results in increased travel time, delays and increased accident risk. Dense snowfall causes poor grip between the road surface and tires and reduces the visibility, resulting in a possible reduction of road capacity by 19-27% and the traffic speed by 11-15 (Agarwal et al. [1]). Keeping roads free from snow is a major part of winter road maintenance in many European countries.
Snow events impact almost the entire continent with an increase in probability toward Northern, Eastern Europe and the Alpine region, where the frequency of days with snow varies between 100-140 days/year. Although the chosen 1 cm snowfall is a relatively low threshold value, even a thin snow cover may cause disruption, particularly in the regions where its probability is reduced. Dense snowfall (≥10 cm/24 h) occurs only sporadically over Western, Southern and most of Central Europe (max. 5 days/year). In Scandinavia the frequency varies between 5-15 days/year, while over the eastern part of the continent and the Balkan Peninsula it rarely exceeds 5 days/year. Heavy snowfall (≥20 cm/24 h) is frequent over Northern Europe (Norway and Iceland) and the Alps: 10-25 cases/year. Nevertheless, the analysis indicates 30-40 cases per year for the rest of Scandinavia, Eastern Europe and some parts of the Balkan Peninsula during 1971-2000.
As the number of freezing days decreases in the future climate, the frequency of snowfall events shows a decreasing tendency as well, with a shift from snow to liquid or mixed precipitation. The multi-model means show 1-5 fewer days of snow in southern Europe (Fig. 1), with changes in the frequency of snow days increasing progressively northward, to 10-20 days in Scandinavia compared to 1971-2000.
The sign of change is consistent among all six RCMs, except in the Mediterranean and the western part of the continent. Contrary to the general decrease in snow days, the probability of extreme snowfall (> 10 cm) increases over large areas of Scandinavia and north-eastern Russia (1-5 days/year). This increase is partly due to the anticipated increase of total precipitation in the future but also due to warmer temperatures, since heavy snowfall tends to occur close to near-zero degrees Celsius. The anticipated decrease in snowfall and frozen precipitation would have a positive impact on road transportation reducing the cost of maintenance and increasing the safety in road transportation in many European countries; however in the Nordic countries, where

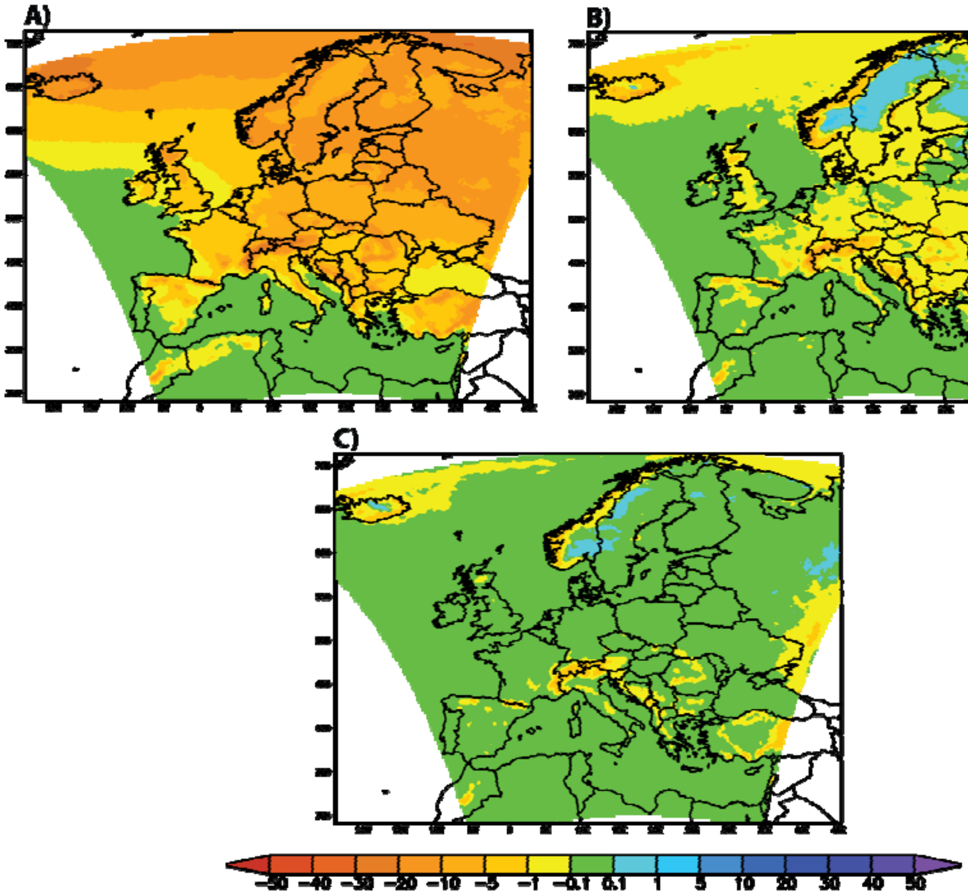

Figure 1. The multi-model mean of changes in changes in annual snowfall days from 1971-2000 to 2041-2070 exceeding (A) 1 cm, (B) 10 cm and (C) 20 cm based on six RCM simulations.

heavy snowfall is already one of the most common disruption factors, it seems to become a more severe phenomenon.

3.2 Cold spell

Low temperatures contribute to the development of slippery conditions; combined with precipitation and wind, this can have a disruptive effect on traffic. However it can be considered a modifier of hazardous conditions for transportation, rather than a main cause.

As expected, the frequency of frost days varies from 100 to 200 per year in Scandinavia, with the highest values in the Scandes (220 days), and decreases southwards, to about 20 days per year (Fig. 2). Most of the continent is free of very extreme cold spells (< 20 °C), except Scandinavia and the NE part of Europe (5-30 days/year).

The simulated cold extremes decline in occurrence substantially by 2070 over the whole continent, and most strongly over Northern Europe. The decrease in the frequency of frost days (0 °C) varies between 20-30 days/year in Northern Europe and decreases gradually towards Southern Europe, with a decrease of 1-5 days/year. Most of the six models agree on the amplitude of change over land. This implies that Finland, Sweden and Norway are likely to experience as many frost days in the 2050s as some mid-latitude countries (such as the Baltic countries, Poland and Ukraine) do in the current climate.

The spatial and temporal analysis of the extreme cold spells also indicates fewer days with temperatures < -20 °C for the affected areas, by 10-20 days/year in Scandinavia, Alps and the north-eastern part of the continent. The RCMs agree on the variation of the upper and lower limits, the most negative change for the extreme cold spell is 1-5 days/year for Northern and North-eastern Europe. The largest differences from the current climate are 30-40 frost days/year in Scandinavia and the Alps, 50 days in the Arctic and Baltic Sea and 10-20 days in Southern Europe.

Fewer days with low temperatures would have a positive impact on road transportation in many regions, conducing to shrinkage in the probability of ice road conditions. On the other hand, in Northern Europe, due to the more frequent near 0 °C temperatures, the increased probability of freeze-thaw cycle would have a negative implication for transport infrastructure, leading to road deterioration.

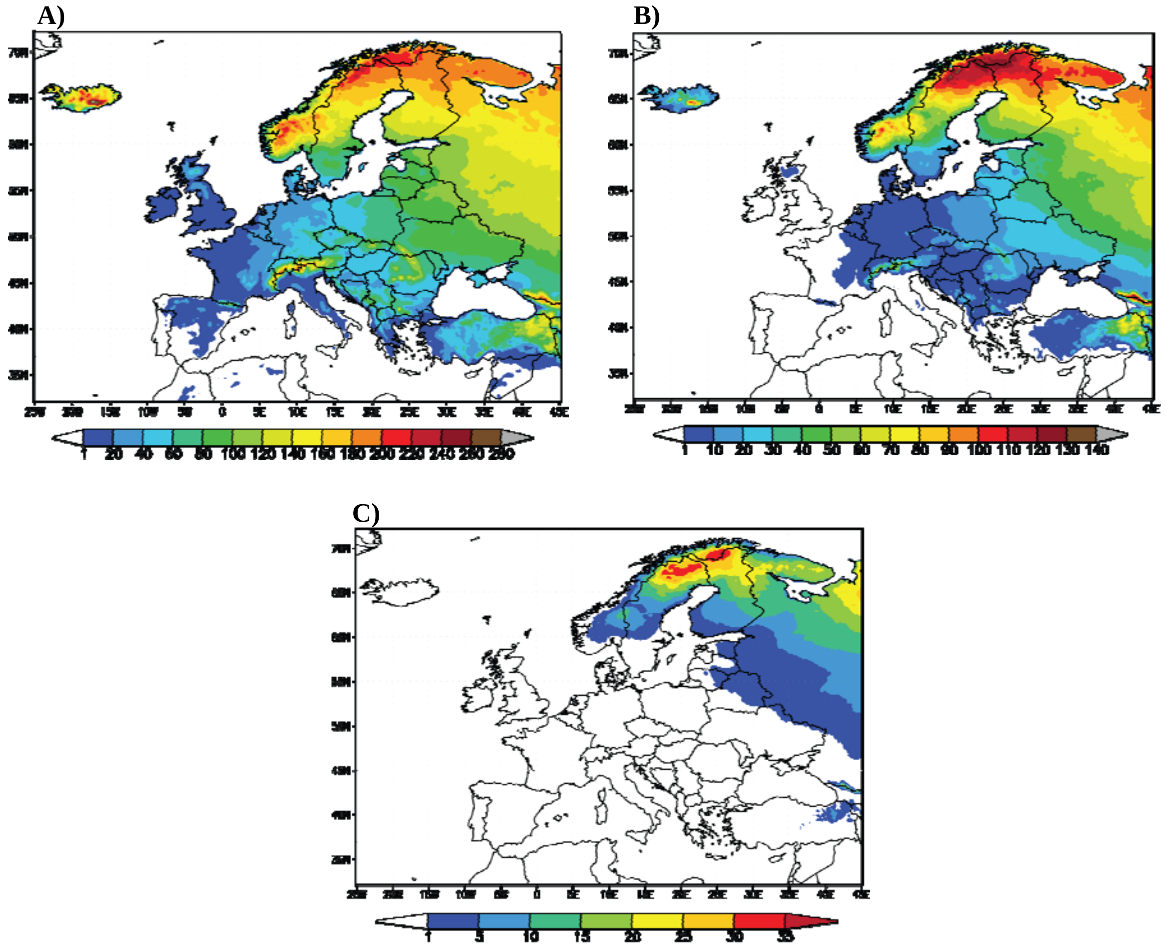

Figure 2. Average number of days per year with daily mean temperature below: (A) 0 °C, (B) -7 °C and (C) -20 °C, during the period 1971-2000 based on E-OBS data.

3.3 Wind

The impact of wind storms on transport network is considerable, all transportation modes being affected. Wind can impede transport operation or damage vehicles and infrastructure leading to significant economic impacts and injuries.

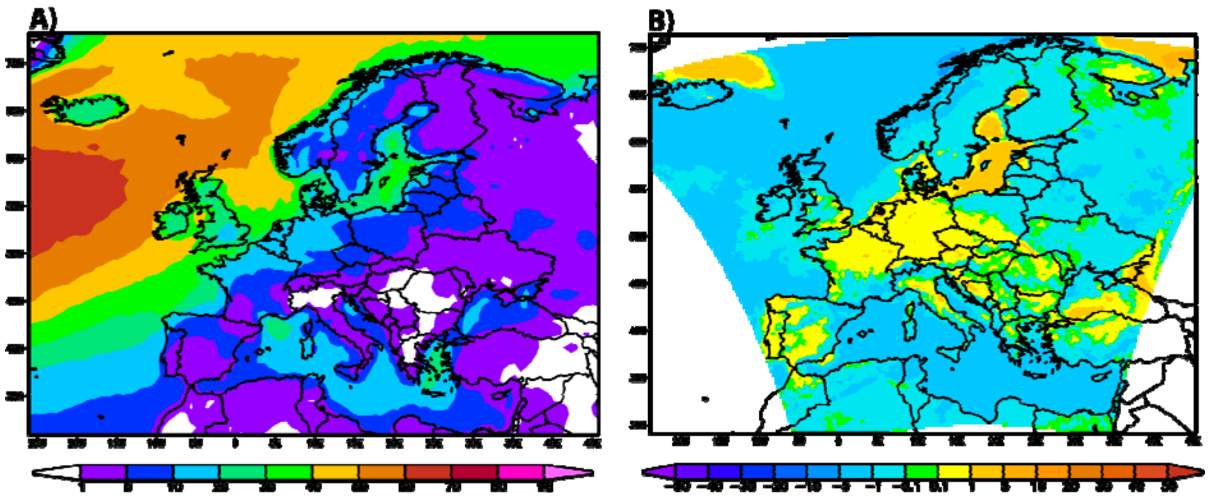

Figure 3. (A) Average number of days per winter (DJF) with wind gust exceeding 17 m/s during 1971-2000 and (B) multi-model mean of changes in wind gust days for the same threshold by 2041-2070.

During the winter season (DJF), extreme wind gusts (≥ 17 m/s) (December-February) are more frequent over the Atlantic (Fig. 3), the most affected land areas being the coastal area (10-20 days/year), British Isles and Iceland (up to 40 days/year). Most of the continent experiences 5-10 days per winter with strong wind gust (17 m/s). Very extreme wind gust events (> 25 m/s) occur rarely and sporadically over Europe.
Considering the expected mean changes in the frequency of wind gust days, the most notable is the decrease over most of the Northern Atlantic and the Mediterranean Sea. The multi-model mean shows a decrease of 1-5 days per winter for all the three impact thresholds. The Northern Atlantic and the Mediterranean basin represent also the more distinctive areas where all the six models agreed on the sign of change.
The multi-model mean indicates that the 17 m/s wind gust threshold will be exceeded 1-5 more days per year over the Baltic Sea in the 2050s, compared to the control 1989-2009 time-frame. Similarly, the increase in winds above the 25 m/s threshold is 0.1-5 days per year. Over land changes in severe wind gust days are less evident. A moderate increase of 1 day/winter can be expected over Western, Central and sporadically Eastern Europe for wind gust ≥ 17 m/s, but overall there is a tendency for a slight decrease (17 m/s) or no clear change in either direction for the higher thresholds (25 m/s and 32 m/s).

3.4 Blizzard

A blizzard is a severe storm condition defined by low temperature, sustained wind or frequent wind gust and considerable precipitating or blowing snow, which can cause damage to structures and, failures in transport control systems, as well as reduced road friction and visibility. A blizzard condition may generate delays and cancellations in all transport modes and increase the rate of accidents.
The analysis indicated relatively low frequency of blizzards during the study period. Blizzard conditions (Fig. 4) occur predominantly over the Alps and Northern Europe (30-40 cases in 21 years). The most affected regions are the western coast of Scandinavia and Iceland, with more than 140 cases in 1989-2010 (~10 cases/year). However, we have to take into account that, due to the difficulties in wind gust prediction and the relatively coarse resolution of ERA-Interim data, the frequency of blizzard events might be underestimated.

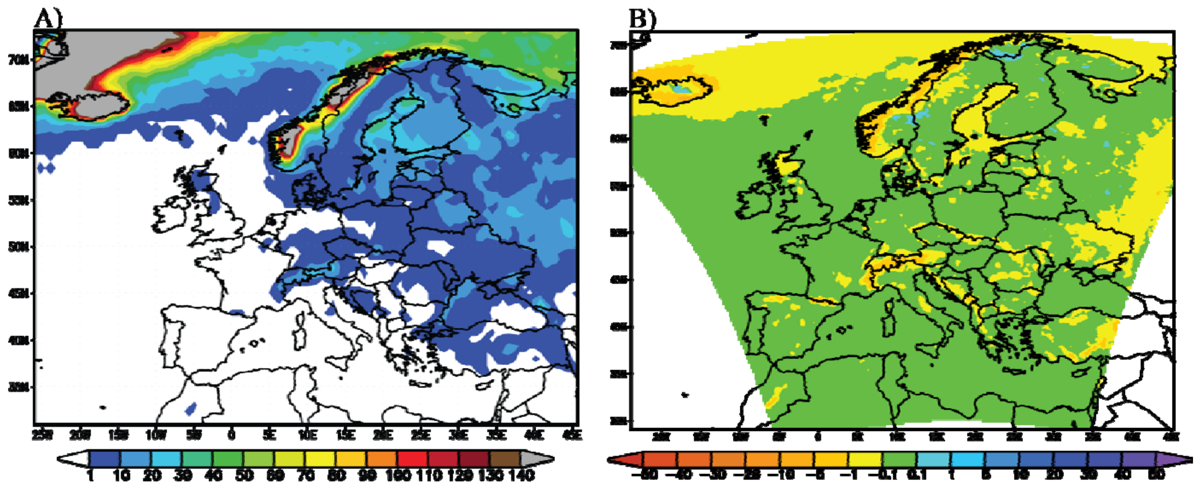

Figure 4. The (A) total number of blizzard events during 1989-2010 and (B) multi-model mean of changes in annual blizzard days by 2041-2070.

Blizzards are expected to become sparser (Fig. 4) in the 2050s with 1-5 fewer days per year compared to the present climate over the North-Atlantic, Iceland, Baltic Sea and its coastal area, the fjord coast of Norway, in the Alps and Pyrenees. Increasing tendencies (by 1 day/year) are sparse and less coherent, though the sign of change is not consistence among the models.

4 DISCUSSION AND CONCLUSION

The analysis of the observed changes in winter temperature, precipitation and wind extremes revealed some common patterns on a European-wide level: high frequency of winter extremes (snowfall, cold spell and winter storms) in Northern Europe and Alpine regions, and a strong continental effect in the frequency of cold spells. Nevertheless, a decline has been observed in the probability of frost days and cold spells during the period studied, with a tendency towards wetter winters in Scandinavia and Eastern Europe. Extreme wind events and blizzards are most common over the Atlantic and its shores and sea areas. In terms of projected future climate the winter extremes are predicted to moderate by 2050s. Cold extremes are expected to become rarer, with a substantial decrease in the north and less accentuated over southern Europe in moderate cold extremes. Snow events in general tend to decrease over the continent. However, extreme snowfall events do not decrease with a similar pattern. Heavy snowfall events (> 10 cm/day) are projected to become more frequent over Scandinavia even if the number of snowy days per year will decrease. For wind extremes, changes are fairly uncertain, with discrepancies among the models.

In general, the most impacted regions by extreme winter weather are the Northern European countries and Alpine region (implying not only the Alps but also the Carpathians, the Pyrenees and the Scandinavian Mountains). However adverse or even extreme winter events might threaten the whole continent resulting in severe disruptions. Since the preparedness of the countries experiencing only rarely severe winter conditions is, in general, lower than of those which are more frequently affected, the severity of disruptions and cost of damages might be more considerable.

The projected changes as well as large natural variability in weather extremes on transportation network will have impacts of both signs. The decline in the frequency of extreme cold and snowfall over most of the continent involves a positive impact on road transportation, e.g. reducing the cost of maintenance and also the frequency of days with slipperiness, thus the accident rate. On the other hand in northern Europe not only the heavy snowfall events are expected to become more frequent but the probability of slippery road conditions may also increase due to the more frequent near 0 °C temperatures. The expectedly more frequent freeze-thaw cycle has a significant negative impact also on the road infrastructure, accelerating road deterioration and resulting in higher maintenance costs and higher life-cycle costs (Andrey and Mills [4]). In the northernmost parts of Europe the higher temperatures would cause the degradation of permafrost that might also affect the road infrastructure. Consequently, even with a general decreasing trend in winter extremes, some regions may have to deal with increasing variability of phenomena. This represents a remarkable challenge for risk management and climate change adaptation requiring new innovation processes besides the old solutions.

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ACKNOWLEGEMENTS
This study is associated with the EU/FP7 project EWENT. We acknowledge the E-OBS dataset and the regional climate scenarios from the EU FP6 project ENSEMBLES (http://ensembles-eu.metoffice.com) and the data providers in the ECA&D project (http://eca.knmi.nl). ERA-Interim data used in this study have been provided by ECMWF.