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Global warming and windstorm impacts in the EU

JRC PESETA IV project – Task 13

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Contents

Executive summary

Windstorms are amongst the most damaging natural hazards in Europe, with approximately 5 €billion of estimated annual losses in the EU. The number of reported windstorms significantly increased over the last decades, yet there is no consensus about a climate-induced trend in windstorms over Europe. Climate model projections of extreme wind are highly uncertain, also because the current generation of climate models still do not resolve spatial and temporal resolution issues. However, but they suggest that windstorms will not become more intense or happen more frequent with global warming over most of the European land, As a consequence, it is expected that risks from windstorms in the EU will not rise due to climate change. Future impacts of wind extremes could be reduced by a range of measures, such as the development and implementation of enhanced windstorm-resilient standards and building codes.

Current effects of windstorms

During the last decades, Europe was hit by a number of highly impacting windstorms that caused a considerable human and economic impact, ranging from human fatalities and injuries to damage to roads, power plants, the agriculture sector, forests, infrastructure, and private properties. Estimated average annual losses for the EU and UK amount to 5 €billion/year (in 2015 values), or approximately 0.04% of total GDP (of 2015). Absolute losses are highest in Germany (850 €million/year), France (680 €million/year), Italy (540 €million/year) and the UK (530 €million/year), while impacts relative to the size of the economy are double the EU average in Bulgaria and Estonia (0.08% of GDP), and 0.07% of GDP in Latvia, Lithuania and Slovenia. Each year approximately 16 million citizens in the EU and UK are exposed to windstorms with an intensity that happens only once every 30 years in present climate, resulting in nearly 80 annual deaths. While in tropical regions an increase in the frequency and intensity of cyclones has been observed in the last decades, in particular from the 1990's, in Europe there is no robust trend in windstorms.

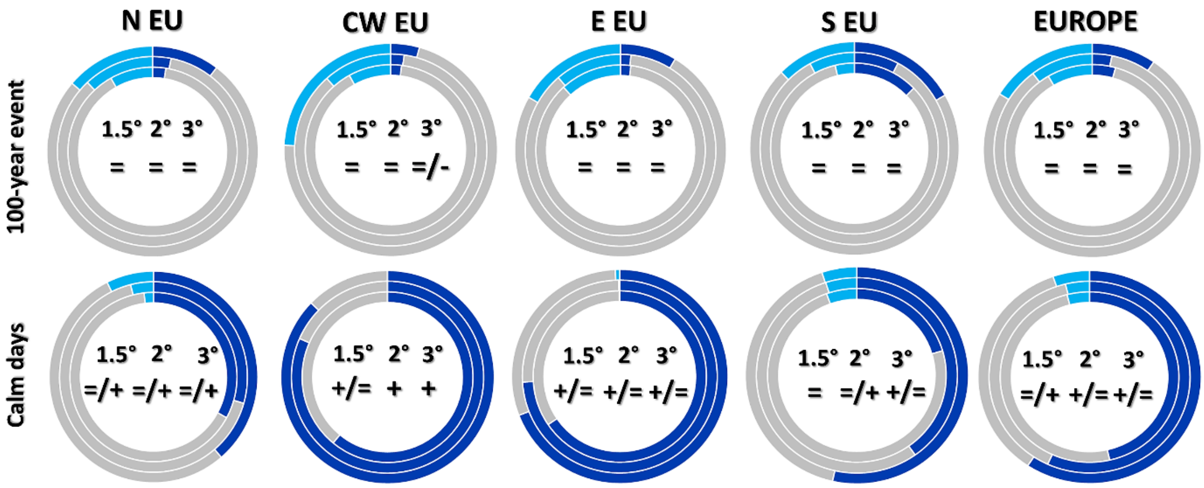


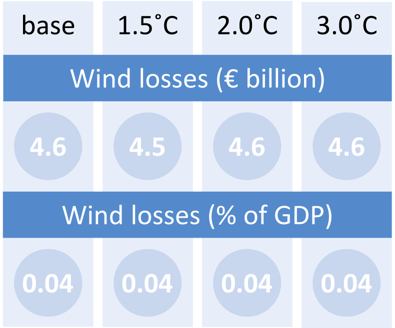
Figure 1. Area fraction (in %) of each region (northern Europe, central-western Europe, eastern Europe, southern Europe) with a significant increase (dark blue), no change (grey) and decrease (light blue) in 100-year wind speed (ensemble median change is significant if >0.3 m/s and at least 2/3 models agree on sign of change) and number of calm days (ensemble median change is significant if >5 days and at least 2/3 models agree on sign of change). Inner (outer) circle represents 1.5°C (3°C) warming.

Wind hazard across Europe in a warmer climate

Recent and pan-European assessments of possible changes in extreme windstorms in view of global warming are lacking and, moreover, none of the earlier iterations of the PESETA project investigated windstorms. According to this study, climate model projections suggest small changes in wind hazard with global warming in Europe. At 3°C warming, maximum wind speeds will likely reduce over 16% of the land area, increase over nearly 10% (including the Alpine areas) and remain relatively stable over the rest of Europe. Southern-Europe is the region with the largest share of the area with an increase in wind extremes (17% at 3°C), while central-western Europe has the largest share of land for which less intense wind extremes are projected (24% at 3°C). Also the number of windy or stormy days does not show significant changes. On the other hand, there is a robust tendency projected towards more calm days (daily maximum wind speed below 3.5 m/s) over most of Europe, in particular over central, west and east Europe (Figure 1).

Economic losses from windstorms assuming no socioeconomic change

The lack of a significant trend in wind hazard with global warming across Europe implies that human and economic impacts will remain stable when assuming that current socioeconomic conditions continue into the future (Figure 2). For most countries impacts also remain stable, yet with 3°C global warming losses could grow to 0.08 of the country GDP (of 2015) in Hungary, Romania and Slovakia compared to 0.06% under present climate. In Estonia, on the other hand, losses could drop from 0.08% of GDP under present climate to 0.05% of GDP with 3°C global warming (see Table 6 in the Annexes for further details).

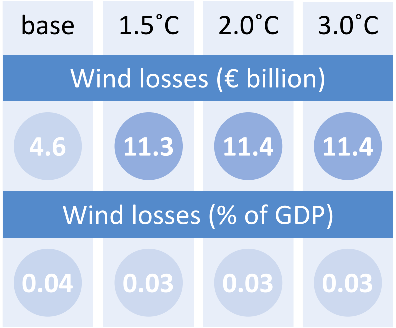


base	1.5˚C	2.0˚C	3.0˚C
Wind losses (€ billion)			
4.6	4.5	4.6	4.6
Wind losses (% of GDP)			
0.04	0.04	0.04	0.04

Figure 2. Annual wind losses for the EU and UK assuming that current socioeconomic conditions continue into the future.

Economic losses from wind storms with socioeconomic change

The projected losses in absolute terms are larger when future socioeconomic change is accounted for compared to when it is assumed, that the current socioeconomic conditions continue into the future, because of the growth of the size of the economy and hence higher values of the exposed assets. By 2050, wind storm annual losses are projected to grow to nearly 7 €billion/year (in 2015 values) for both 1.5 and 2°C global warming. By the end of this century this further grows to more than 11 €billion/year, with slightly higher impacts for higher levels of warming (Figure 3). Future wind-induced damage expressed as a share of the size of future economies show a small decrease because building stock and replacement costs grow somewhat slower than GDP.



base	1.5˚C	2.0˚C	3.0˚C
Wind losses (€ billion)			
4.6	11.3	11.4	11.4
Wind losses (% of GDP)			
0.04	0.03	0.03	0.03

Figure 3. Annual wind losses for the EU and UK assuming socioeconomic conditions in 2100 according to the 2015 Ageing Report.

Resilience to wind extremes

Even though our projections indicate that wind hazard and risk will likely not change in Europe with global warming, increasing resilience to present wind extremes could further reduce impacts on future societies. There are a wide range of measures that could be taken, such as increasing windstorm forecast accuracy and warning time, improving storm readiness, emergency communications and response, as well as structural measures for wind-proofing infrastructures, which in the EU could be stimulated by amendments of Eurocodes.

Approach

Projections of daily wind speed under a high emissions scenario (RCP8.5) and moderate mitigation scenario (RCP4.5) were used in order to estimate changes in wind hazard between baseline (1981-2010) climate and at global warming levels of 1.5, 2 and 3°C above preindustrial levels. Wind damage functions, which relate the total construction stock with wind speed and economic losses, as well as reported fatalities, were derived from past wind events and their reported impacts. In the absence of information on future vulnerability, these impact relations were kept constant in the scenarios. The damage and mortality relations were then applied in a static-economic scenario, in which wind hazard at the different warming levels was applied to the present population and construction stock. We also combined the projections of wind hazard at the warming levels with projections of exposed construction assets and population in 2050 and 2100 according to the 2015 Ageing Report. As it is very unlikely that 3°C warming will happen by mid-century, this warming level was only combined with 2100 society in the dynamic economic scenario. The use of the static and dynamic economic scenarios allows disentangling the effects of climate change and exposure dynamics on future windstorm losses.

An important limitation of the analysis is the spatial resolution of the wind data, which is too coarse to capture local severe windstorms. The current generation of climate models also have a rather poor physical representation of wind dynamics. Further, in the absence of wind gust data at sub-daily time steps we used daily maximum wind speed as a proxy of windstorms. It is yet unclear if these limitations affect current projections of wind hazard in view of global warming.

1 Introduction

Cyclones and extreme windstorms represent the most damaging natural hazard at global scale, causing approximately one third of total natural disaster losses and two thirds of insured losses. Though Europe is not frequently hit by cyclones, but only by dust storms, extratropical cyclones and windstorms (Foreman, 2018), storms together with floods are the costliest naturel hazard in Europe (EEA, 2017; Sharkey et al., 2019). Between 1980 and 2016 they accounted for 31% of total losses and 63% of insured losses, but only 3% of total fatalities recorded. Similar numbers have been reported at global scale, with windstorms accounting for one third of total losses by natural disasters and more than two thirds of insured losses (Berz, 2005). The impacts caused by extreme windstorms include mortality and serious injuries, tree fall, flying debris, damage to properties and infrastructure, disruption of electricity lines, traffic interruption, and stresses on wind turbines, among others (Forzieri et al., 2018).

Recently, a few severe windstorms in Europe were reported in the Copernicus Emergency Management Service (EMS[1]), such as the autumn 2018 event in northeastern Italy that partially destroyed the woods famous for the Stradivari's violins. Though the media tend to emphasize such events, literature suggests the lack of a general trend in windstorm frequency and intensity over Europe (Barredo, 2010; Feser et al., 2015; Tobin et al., 2015; Cronin et al., 2018; Spinoni et al., 2019). Results of trend analysis in storm activity critically depend on the time period analysed due to decadal climate variability and detecting long-term trends is hampered by the inhomogeneity in historical wind measurements. At regional scale, in the last decades a slight increase of storminess over North Atlantic and northwestern Europe and a decrease in southern Europe (Feser et al., 2015) and the Mediterranean (Nissen et al., 2014) has been reported, and a slight upward trend in winter windstorms in Central Europe (Leckebusch et al., 2008).

With global warming climate extremes are expected to intensify (Forzieri et al., 2016). Some studies report a likely small increase of storm intensity and frequency in the North Atlantic, northwestern, and western Europe (Della Marta and Pinto, 2009; Feser et al., 2015), a decrease in southern Europe (Nissen et al., 2014), and contradicting trends over northern and eastern Europe (Pryor et al., 2010). Recent and pan-European assessments of possible changes in extreme windstorms in view of global warming are lacking. Also in PESETA III (and earlier iterations of the project) windstorms were not analysed.

Human and economic losses from storms depend not only on the dynamics and nature of the storm, but also on the exposure of human population and assets, their vulnerability and the coping capacity of local and regional communities. The lack of reliable and validated data on vulnerability to windstorms is a gap that needs to be filled in order to better understand the risk associated to windstorms. Existing aggregated loss indexes for large-scale applications typically correlate population density and wind speed with reported damage (e.g., Pinto et al., 2012). There exist more detailed models for specific infrastructures, such as wind=fragility curves for glass façades (Lima-Castillo et al., 2019) or power transmission networks (Scherb et al., 2019), yet their application is typically limited to smaller scales and they only capture the infrastructure-specific impacts.

Given the magnitude of impacts of windstorms in Europe and the lack of pan-European projections of this hazard and the consequent risks, the PESETA IV windstorm analysis aims at filling this gap. We investigate the correlation between reported impacts and windstorms over past decades and estimate the possible changes in view of global warming and socioeconomic projections. Reported economic impacts of windstorms are dominated by damage to infrastructures, while losses to ecosystems typically are not included in loss figures. Hence, loss estimates herein do not capture these effects. Disturbances of forests due to windstorms, however, are covered in the forest ecosystems task of PESETA IV. The energy task of PESETA IV further evaluates the effect of changes in wind regime on wind power potential in Europe. For the wind analysis in both of these tasks the same underlying wind data from the climate models are used as in the windstorm analysis presented herein.

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[1] https://emergency.copernicus.eu/mapping/list-of-components/EMSR334

2 Methodology

This report presents projections of risk of extreme winds for Europe in view of global warming. As an indicator of wind hazard we used daily maximum wind speed, with a focus on its most extreme values that have the potential to result in human impacts and damage to infrastructures and assets. To this end, we selected wind speeds above the 98.5th percentile and fitted an extreme value distribution to these data with non-stationary extreme value analysis. The extreme value analysis allows relating return levels (RLs) with return periods (RPs) for extreme wind speed over Europe for the baseline and future periods. The return period expresses how frequent an event can be expected to happen, whereas the return level is the corresponding magnitude of the event. The longer the return period, the rarer is the event, but if an event of a given RP shows a shorter RP in the future, it means that such event will be more frequent. The RPs are expressed in number of years, the RL is the wind speed (in m/s) corresponding to the RP. In this study, we analysed extreme events corresponding to RPs from 1 year to 1000 years. As illustrative example, we show results for 10-year and 100-year return periods. To compute changes in hazard between the baseline and future periods, we used the ensemble median. To evaluate the robustness of the projections, we used the agreement in sign between simulations: the change is significant (in sign) if at least two thirds of the models agree on an increase (or decrease) in extreme wind speed.

We appraised vulnerability to extreme winds on the basis of damage records collected from disaster databases during the period 1981-2016. The damage data associated to the reported events were used to calibrate damage functions that correlate the reported loss with the return period of the event derived from weather reanalysis and the value of total construction of the area where the event caused impacts. Total construction was used as a proxy of exposure, as damage from wind is typically dominated by infrastructure damage. Information on the value of the total construction stock was obtained from EUROSTAT[2]. Projections of the total construction stock are not available. Given that it shows a strong correlation with GDP, future total construction values were obtained by scaling baseline values with the projected changes in GDP based on the ECFIN 2015 Ageing Report (EC, 2015)[3]. For the human impact (mortality) we derived mortality rates from the total number of fatalities reported per country over the period 1981-2016 and the number of people exposed to windstorms (corresponding to a 50-year intensity or more severe). Population projections are also according to the 2015 Ageing Report. The national scale socioeconomic data were further downscaled by the LUISA Territorial Platform[4].

We evaluated windstorm hazard and risk in Europe throughout the 21st century by comparing impacts under baseline (1981-2010) climate with those under global warming levels (GWLs) of 1.5, 2 and 3°C above preindustrial levels. We evaluated wind impacts under GWLs on today's society (static economic analysis) as well as on Europe in 2050 and 2100 for the EU Reference economic scenario (2015 Ageing Report projections. This allows understanding windstorm risk if climate conditions under different levels of warming would be imposed on today's society, without any assumptions on socioeconomic developments over long time spans. In addition, we also assess the impacts at different warming levels on society in 2050 and 2100 for the EU Reference socioeconomic scenario (2015 Ageing Report projections). Comparison of the static and dynamic economic analyses allows disentangling the effects of climate and socioeconomic changes. The vulnerability derived from recent windstorm events is assumed constant in the projections, hence the results presented do not include any additional adaptation of sectors to changing maximum wind speed conditions. Our hazard analysis includes all EU member states plus a number of neighbouring countries (Iceland, Norway, and Switzerland and Balkan countries). Economic impacts are presented for EU countries and the UK. More details on the methodology can be found in Annex 1.

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[2] http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nama_10_nfa_fl&lang=en

[3] During the PESETA IV project, the 2018 Ageing projections became available but they could not be incorporated. Compared to the 2015 Ageing Report, GDP growth projections are slightly lower over the period 2025-2050 and marginally higher during 2055-2070. These updated projections do not affect the main conclusions of this report.

[4] https://ec.europa.eu/jrc/en/luisa

3 Findings

3.1 Wind losses in the recent past

We analysed reported damage from about 2000 wind-related disaster records collected over 1981-2016 in the Munich RE's NatCatSERVICE disaster database. Figure 4 shows the evolution in time of the total number of reported wind events, fatalities, and damage (expressed in 2015 €billion) per year in Europe between 1981 and 2016. The total number of reported events in time shows a significant increasing trend in the analysed period. The total reported fatalities caused by wind over the period 1981-2016 sums up to an average of 80/year. Reported fatalities do not show a statistically significant trend. The total reported economic damage caused by wind over the period 1981-2016 sums up to nearly 138 €billion or an average of 3.7 €billion/year. Reported damage shows a slight increasing trend in time. With a lack of general trend in extreme windstorms over this period in Europe, this relates predominantly to more value exposed due to economic growth.

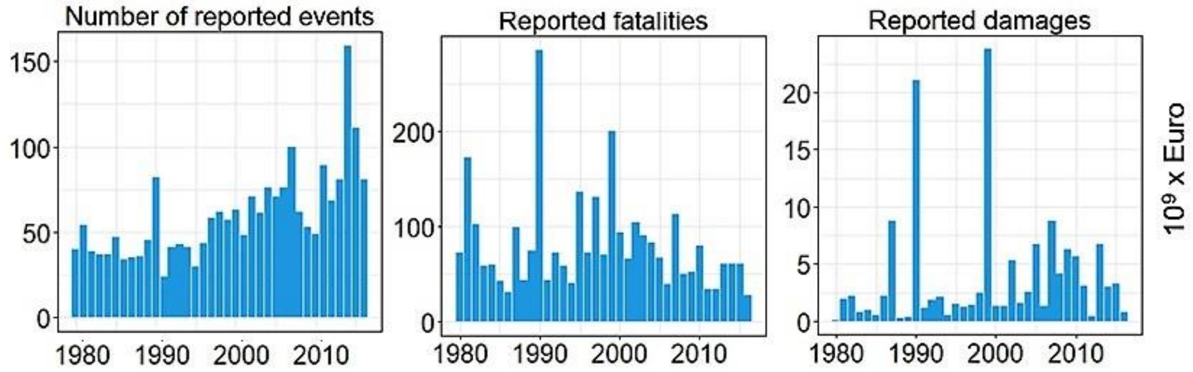

Figure 4. Evolution in time of the total number of reported wind events, fatalities, and damage in Europe between 1981 and 2016 (from NatCatSERVICE disaster database).

3.2 Wind hazard projections

Figure 5 shows the projected changes in wind speed of a present 10-year and 100-year daily maximum wind speed between the baseline and warming levels of 1.5, 2°C and 3°C. The projected changes in maximum wind speed are very small both in absolute values and relative terms. There is also no homogeneous spatial pattern in the projected changes in wind extremes over European lands. The projected changes slightly increase in absolute values with global warming level and they are overall statistically somewhat more robust, but still no clear general pattern is present. However, in particular for higher intensity wind speeds (exemplified by the 100-year wind speed) at a global warming level of 3°C, some robust patterns emerge: a decrease in return level (meaning less severe windstorms) over most of Iceland, north-western France, southern Portugal, north-eastern Poland, and southern UK. Oppositely, an increase in wind hazard is projected over mountainous areas in Scandinavia and the Alps, and in southern Italy and scattered areas in central and eastern Europe (e.g., Hungary and Romania).

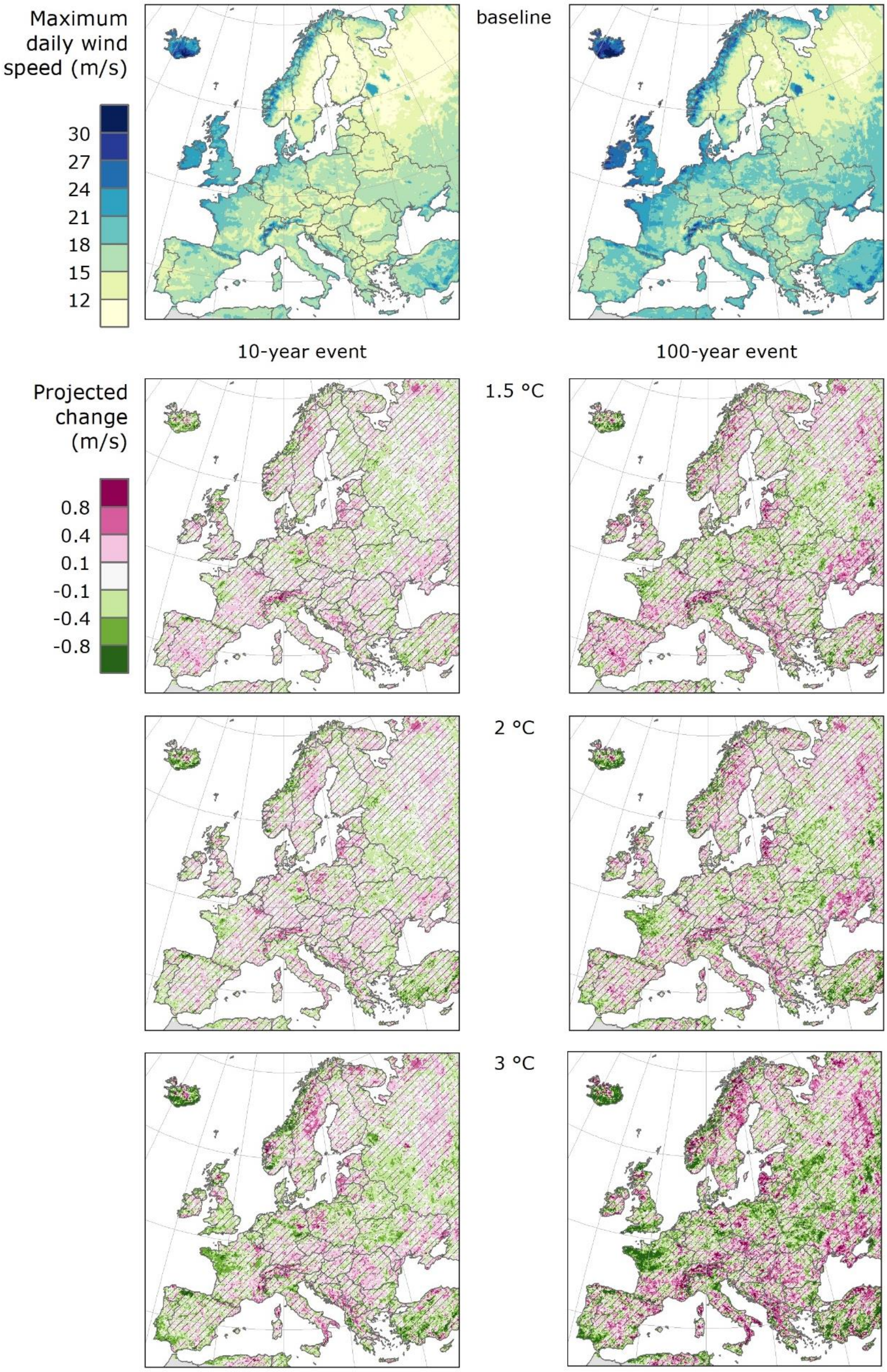

Figure 5. Baseline 10- and 100-year maximum daily wind speed and projected change for different global warming levels. Dashed lines represent no-robust changes where less than two third of the simulations agree on the sign of change.

The pan-European and macro-regional scale summary (Figure 6,

Table 5) shows that at 1.5°C global warming over nearly 90% of the European land area the projected changes are negligible (<0.3m/s) or not robust (less than two thirds of the simulations agree on the sign of change). The area that shows a robust change in extreme winds grows with the level of warming. At 3°C, in approximately 25% of Europe there is a robust (though not strong) change in extreme winds projected, with for 15% of the area less extreme winds and for 10% of the area higher maximum wind speeds. Only in southern Europe, the area with a signal towards more severe wind storms is larger (16.7%) than the area with less intense wind extremes (12.3%). In central and western parts of Europe a robust and significant increase in intense winds is projected for less than 5% of the area, compared to a robust significant decrease over nearly 25% of the area.

Our projected changes in wind hazard that are small and spatially heterogeneous confirm similar findings reported by Tobin et al. (2015) and Moemken et al. (2018). Overall, we see a slight tendency towards less frequent and severe windstorms over European land areas (especially in spring and summer), but with low statistical confidence. The increase in calm days (wind speeds below 3.4 m/s) is more pronounced especially in central-western and eastern Europe (Figure 8). The small projected changes in wind extremes projected could relate to the spatial resolution and poor physical representation of winds in CMIP5-generation climate models (Wang et al., 2014), especially over lands. The new CMIP6 generation of climate simulations (Eyring et al., 2016), which are currently under development, could help improving the wind hazard projections analyses.

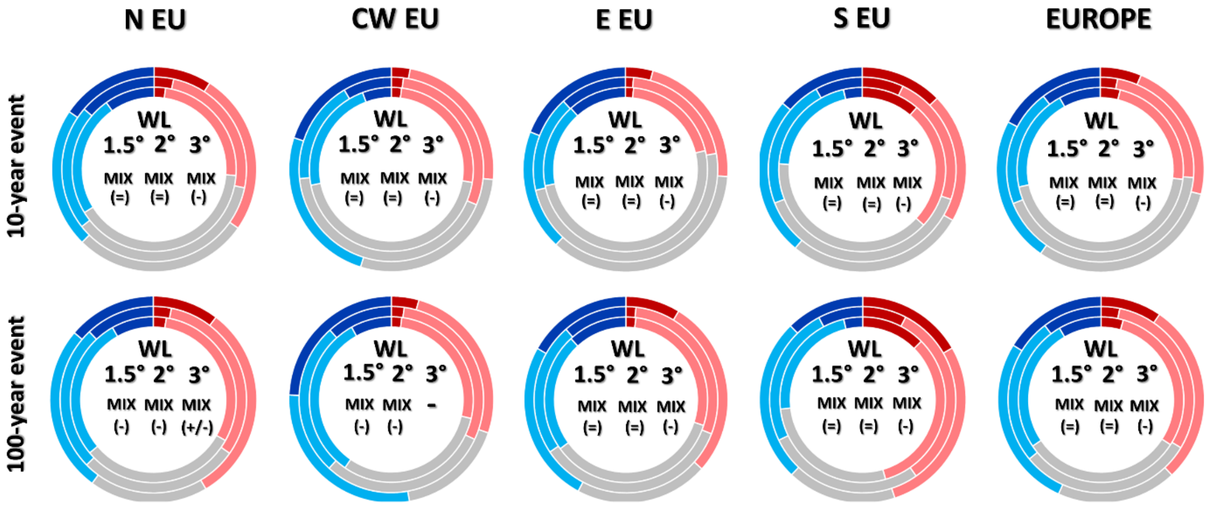

Figure 6. Projected changes compared to baseline in wind hazard for Europe and macro-regions. Shown are percentages of the area with changes in 10- and 100-year windspeed that are negligible (ensemble median change <0.3 m/s, grey), not negligible but not robust (ensemble median change >0.3 m/s but <2/3 of models agree on sign of change, pink and light blue), and robust (ensemble median change >0.3 m/s and ≥2/3 models agree on sign of change, dark red and blue). Inner (outer) circle represents 1.5°C (3°C) warming.

3.3 Wind impact projections

Wind impact projections under static socioeconomic conditions (Table 1) are in line with the wind hazard projections, and consequently the projected changes in wind-induced damage with increasing levels of warming are very small. Damage from extreme wind on future societies will grow in absolute terms, but this relates to the increase in the value of the total construction stock in a growing economy. As a consequence, the differences in impacts between warming levels on European societies in 2050 and 2100 are similarly very small. When damage is expressed as a share of GDP, they become somewhat smaller for future societies. This relates to the exponent of the total construction in the damage function, which is smaller than one. Hence, wind damage grows at a lower rate as the projected rise in GDP. For all levels of warming considered, none of the EU countries is expected to have annual windstorm this century that are larger than 0.06% of their GDP.

Very small changes are also projected for the Expected Annual People Exposed (Table 2). Without strong demographic trends in Europe and the very small changes in wind hazard with global warming, the number of people exposed to wind extremes remains similar in the EU. As a consequence, also windstorm fatalities show minor changes. It should be noted that these estimates of economic damage and fatalities are based on present vulnerability estimates (i.e., the damage function and mortality rates derived from past disasters) under all scenarios. If the trend of declining vulnerability with increasing wealth observed over the last decades in high-income countries (Formetta and Feyen, 2019) continues, it is expected that future relative impacts of wind extremes to EU societies will be lower than today.

Table 1. Ensemble median Expected Annual Damage (EAD, expressed in 2015 €million) for the baseline (1981-2010) and warming levels for the alternative socioeconomic scenarios.

	Base society				2050 society		2100 society		
Country	**base**	**1.5°C**	**2.0°C**	**3.0°C**	**1.5°C**	**2.0°C**	**1.5°C**	**2.0°C**	**3.0°C**
Austria	116	126	137	128	191	206	305	329	308
Belgium	121	118	120	111	187	190	326	330	305
Bulgaria	29	29	26	31	39	34	55	48	59
Cyprus	6	7	6	6	15	14	26	24	21
Croatia	29	25	28	34	38	44	55	63	76
Czechia	91	80	84	93	115	122	196	208	231
Denmark	93	75	89	82	137	161	245	288	266
Estonia	12	11	9	9	16	14	24	20	18
Finland	110	109	99	100	158	144	269	244	247
France	682	704	709	752	1,084	1,088	1,920	1,928	2,046
Germany	854	797	844	896	1,042	1,103	1,554	1,646	1,748
Greece	72	71	68	68	81	78	113	110	110
Hungary	62	61	65	76	88	93	128	136	159
Ireland	83	80	78	63	135	130	251	243	197
Italy	541	528	512	535	788	765	1,262	1,226	1,278
Latvia	15	13	13	12	18	17	27	26	25
Lithuania	22	20	22	18	27	30	43	47	39
Luxembourg	15	14	15	16	25	28	45	51	52
Malta	3	4	3	2	10	8	15	13	9
Netherlands	188	155	157	149	223	226	373	378	357
Poland	223	200	214	204	311	333	410	439	419
Portugal	56	67	57	69	94	80	132	112	133
Romania	83	95	90	99	131	125	193	184	201
Slovakia	43	43	45	55	67	70	101	104	127
Slovenia	24	24	25	27	34	37	55	60	63
Spain	324	336	329	355	555	538	883	856	929
Sweden	170	184	191	177	321	335	614	640	596
United Kingdom	528	550	552	473	899	900	1,639	1,640	1,403
EU and UK	4,594	4,528	4,588	4,641	6,829	6,913	11,260	11,393	11,422

Table 2. Ensemble median Expected Annual People Exposed (EAPE, in 1000 people) for baseline (1981-2010) and warming levels for the alternative socioeconomic scenarios.

	Base society				2050 society		2100 society		
Country	**base**	**1.5°C**	**2.0°C**	**3.0°C**	**1.5°C**	**2.0°C**	**1.5°C**	**2.0°C**	**3.0°C**
Austria	278	282	287	269	328	331	311	315	294
Belgium	363	340	339	343	457	456	497	496	502
Bulgaria	236	239	237	275	188	186	131	129	152
Cyprus	27	27	25	22	32	29	33	31	26
Croatia	126	128	142	162	110	123	84	93	106
Czechia	347	324	340	355	344	360	312	326	339
Denmark	169	153	154	142	176	176	191	191	177
Estonia	36	35	32	28	32	28	26	23	21
Finland	172	173	174	169	197	197	202	202	196
France	2,032	2,080	1,945	1,975	2,396	2,239	2,570	2,402	2,438
Germany	2,660	2,581	2,596	2,503	2,402	2,406	2,024	2,027	1,947
Greece	310	303	291	282	260	250	198	190	184
Hungary	329	332	358	401	316	342	256	278	311
Ireland	146	155	146	143	168	159	190	179	176
Italy	1,840	1,778	1,758	1,865	2,022	1,997	1,825	1,803	1,912
Latvia	67	66	59	52	45	41	37	33	29
Lithuania	98	95	94	80	60	59	51	51	43
Luxembourg	16	19	20	20	37	40	48	52	52
Malta	11	10	9	9	11	10	10	9	9
Netherlands	549	533	528	502	562	557	545	540	513
Poland	1,275	1,200	1,234	1,110	1,089	1,121	752	775	695
Portugal	303	346	264	241	285	218	224	171	156
Romania	667	667	687	793	595	614	443	457	529
Slovakia	183	172	178	209	155	160	117	121	142
Slovenia	70	73	80	87	75	82	67	73	79
Spain	1,399	1,450	1,295	1,218	1,400	1,248	1,260	1,123	1,055
Sweden	303	301	303	262	383	384	467	467	405
United Kingdom	1,996	2,073	2,092	1,968	2,538	2,565	2,802	2,832	2,672
EU and UK	16,010	15,935	15,666	15,485	16,662	16,377	15,672	15,387	15,158

4 Conclusions

The wind hazard projections show that with global warming there will likely be no significant change in extreme wind-related events over most of the European territory. On the other hand, a robust increase in calm days is projected almost everywhere. This could have positive consequences for various sectors, from wind farm power generation to tourism and river transportation. We used a large number of the most recent high-resolution climate simulations available for Europe. However, present climate models still do not resolve some model and resolution issues, which make projections of future wind, and especially the extremes, highly uncertain. There is a clear need for very high spatial and temporal resolution wind data (the best option would be of wind gust instead of maximum wind speed), both for the past and future. In order to improve the projections – which does not necessarily mean larger and more robust changes – the new generation of climate models (i.e., the CMIP6) could help.

The likely small changes expected in wind extremes with global warming will result in negligible changes in risks associated to windstorms. The projected changes in exposure (population and assets) in Europe also do not dramatically change future wind risk projections. Our analysis assumes static vulnerability. This means that the human mortality and economic loss rates derived from reported impacts of past windstorms are assumed to be constant under the different scenarios. Even though that wind hazard and risk will likely not strongly rise with global warming, the risk to future societies could be further reduced by increasing resilience to extreme winds.

Possible adaptation measures include improved design of infrastructure, such as the siting and orientation of buildings, the angling of roofs so that they slope down to face the prevailing wind direction, taking advantage of adjacent shielding, avoiding excessive roof overhangs and nearby hazardous objects such as mature trees and overhead distribution cables. Also the development and use of new materials can make buildings and infrastructure more resilient against extreme wind gusts. In the EU, the wind-proofing of infrastructure could be further stimulated through potential amendments of Eurocodes with regard to structural design addressing relevant impacts of windstorms, both general and material-specific. Buildings that require continuity of services such as power, for instance healthcare buildings, should be protected against interruptions to power supplies. Other measures include the removal of debris and old trees close to traffic roads, a strategic plan to plant broadleaved trees close to houses, schools, and hospitals instead of tall conifers, and the capillary teaching of actions to take during a windstorm emergency.

Annexes

Annex 1. Extended methodology

A1.1 Weather reanalysis and climate projections

The new ERA5 reanalyses dataset, provided by the ECMWF (European Centre for Medium-Range Weather Forecasts), is the most recent meteorological reanalysis dataset. It includes estimates of a range of atmospheric parameters, including air temperature, pressure, wind, humidity and ozone at different altitudes, and surface parameters such as rainfall, soil moisture, sea-surface temperature. The resolution of the dataset is 0.25°. In this study, we downloaded maximum wind speed at hourly temporal resolution data for Europe from 1979 to 2018. These data were used to analyse windstorms in the past and link them with reported losses.

Projections of wind hazard (daily maximum wind speed at 10-m) with global warming are based on two Representative Concentration Pathways (RCPs): RCP4.5 and RCP8.5. RCP4.5 may be viewed as a moderate-emissions-mitigation-policy scenario and RCP8.5 as a high-end emissions scenario. Statistical and quantitative hazard analyses in this report are performed over 30-year time periods. The reference scenario spans the period 1981-2010, hereinafter referred to as “base”. We compare impacts for the baseline with those over 30-year time slices centred on the year that global average temperature is 1.5, 2 and 3°C above preindustrial temperature (Table 3). The 1.5°C and 2°C warming scenarios are explicitly considered in the Paris Agreement, while a 3°C global warming is a scenario that could be expected by the end of the 21st century if adequate mitigation strategies are not taken.

Table 3. Regional climate projections used in the wind hazard and impact analysis and corresponding years of exceeding 1.5, 2 and 3 °C global warming.

RCM (R)	Driving GCM (G)	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
		1.5 °C		2 °C		3 °C	
CCLM4.8-17	CNRM-CERFACS-CNRM-CM5	2035	2029	2057	2044		2067
	ICHEC-EC-EARTH	2033	2026	2056	2041		2066
	MPI-M-MPI-ESM-LR	2034	2028	2064	2044		2067
HIRHAM5	ICHEC-EC-EARTH	2032	2028	2054	2043		2065
WRF331F	IPSL-IPSL-CM5A-MR	2023	2021	2042	2035		2054
RACMO22E	ICHEC-EC-EARTH	2032	2026	2056	2042		2065
RCA4	CNRM-CERFACS-CNRM-CM5	2035	2029	2057	2044		2067
	ICHEC-EC-EARTH	2033	2026	2056	2041		2066
	IPSL-IPSL-CM5A-MR	2023	2021	2042	2035		2054
	MOHC-HadGEM2-ES	2021	2018	2037	2030	2069	2051
	MPI-M-MPI-ESM-LR	2034	2028	2064	2044		2067

For each RCP an ensemble of 11 EURO-CORDEX combinations of Global Climate Models (GCM) and Regional Climate Models (RCM) were used (Jacob et al., 2014). Wind hazard conditions at 1.5 and 2°C warming were derived from an ensemble of 22 climate projections (11 RCP4.5 and 11 RCP8.5 members), whereas the ensemble projections for 3°C warming are based on RCP8.5 only, as 10 out of 11 RCP4.5 climate simulations do not reach 3°C warming.

It should be noted that we derived climate at global warming levels from transient climate projections, which may differ from stabilized climate at those warming levels. Studies (e.g., Maule et al., 2017) suggest that the effect of pathway to global warming levels is small compared to the models' variability, expect for strongly not time-invariant variables such as sea level rise.

A1.2 Socioeconomic projections

We performed the wind risk assessment with static socioeconomic conditions as well as with projections of socioeconomic development in Europe. The static approach provides information on how climate and consequent wind conditions at different global warming levels would affect today's societies in Europe. For the dynamic economic assessment we focus on 2050 and 2100. At mid-century we evaluate losses of 1.5 and 2°C warming on 2050's economy (as 3°C is unrealistic by mid-century) and at the end of the century we consider the effect of the three warming levels on 2100's economy.

The projections of socioeconomic development in Europe are based on the ECFIN 2015 Ageing Report, further referred to as EU Reference Scenario. This scenario acts as a benchmark of current policy and market trends in the EU. High-resolution land use and population projections based on the EU Reference Scenario were derived with the LUISA modelling platform (Jacobs-Crisioni et al., 2017).

As the Ageing report deals with projections only to the year 2060, the projections have been extended to the year 2100. Regarding the GDP projections, the Ageing Report assumes that two out of the three determinants of economic growth, technical progress and capital accumulation, would reach a steady state (with constant growth rates) by the year 2060. That has been assumed as well for the following decades. The third contributor to growth (the labour input) has been assumed to evolve in a proportional way with respect to population (i.e. same growth rate). That means ignoring possible changes in the labour markets conditions, such as changes in the participation rates or the employment rate. The population projections for 2061-2100 are taken from the latest United Nations demographic report (medium variant), and they are explicitly considered in the computation of the economic growth figures (more details can be found in Ciscar et al., 2017).

A1.3 Wind indicator

Wind-related damage is often caused by wind gusts (Francis and Gillespie, 1993; Pryor et al., 2010; Schwierz et al., 2010), defined as a sudden increase of wind speed. The wind gust is not available from EURO-CORDEX climate projections and instead we used the daily maximum wind speed as proxy (Rockel and Woth, 2007). Daily maximum wind speed was obtained as the maximum speed among sub-daily wind speed values from the reanalysis datasets and as a direct quantity from EURO-CORDEX simulations. Using maximum daily wind speed instead of wind gust may introduce a bias, in particular dealing with tropical cyclones (Powell et al., 2003) or the extratropical cyclones as the Medicanes, the Mediterranean hurricanes (Cavicchia et al., 2014), but they are extremely rare over European lands. Another limitation is that the spatial resolution of the wind data may not capture local windstorms, and so windstorm peaks are likely to be underestimated. Further, local orography cannot be fully reproduced with 0.11° or 0.25° data and sub-hourly measurements would be preferable.

We focus only on extreme wind events, which are likely to cause the largest human impact and damage to infrastructures (Forzieri et al., 2018) and other assets. Our approach follows that by Forzieri et al. (2016), i.e. we considered only windstorms on the end-tail (98.5th percentile) of the statistical distribution of daily maximum wind speed over that location, applying a Peak over Threshold analysis and fitting the extremes with a Generalized Pareto Distribution (Hosking and Valli, 1998). To minimize extrapolation errors, we opted for a non-stationary extreme value analysis (EVA) over the full length of the climate projections (Mentaschi et al., 2016).

The extreme value analysis (EVA) allowed relating return levels (RLs) with return periods (RPs) for extreme wind speed over Europe for the baseline and future periods. The return period expresses how frequent an event can be expected to happen, whereas the return level is the corresponding magnitude of the event. The longer the return period, the rarer is the event, but if an event of a given RP shows a shorter RP in the future, it means that such event will be more frequent. The RPs are expressed in number of years, the RL is the wind speed (in m/s) corresponding to the RP. In this study, we analysed extreme events corresponding to RPs from 1 year to 1000 years. As illustrative example, we show results for 10-year and 100-year return periods.

To compute changes in hazard between the baseline and future periods, we used the ensemble median. To evaluate the robustness of the projections, we used the agreement in sign between simulations: the change is significant (in sign) if at least two thirds of the models agree on the increase (or on the decrease). In next subchapters, we present also regional statistics about projected changes.

The use of wind data is becoming more and more important for different sectors, an example is power generation in wind farms by wind turbines (Vautard et al., 2014), which operates at best conditions with wind speed between two critical values (Hansen, 2015). In order to complement the wind hazard analysis with other frequently used indicators, we compute additional wind indicators and we investigate their changes between the baseline and the warming levels (and fixed future periods).

A1.4 Vulnerability assessment

In this study, we assess vulnerability to windstorms by correlating observed impacts from windstorms with the intensity of these events estimated based on reanalysis wind data. To do that, we obtained impact data from Munich Re's Natural Catastrophe Statistics dataset (NatCatSERVICE[5]). This database is structured at country scale, with sometimes more geographical precision of the area affected. For Europe over the period 1981-2016 it contains information on more than 2,000 wind-related events, for which damage is reported in about 40% of the cases. Trends in these data have been evaluated for statistical significance using the Mann-Kendall test. This shows that reported losses typically underestimate true wind losses. There is no disaggregation of the losses between different sectors. This is a main limitation, together with incomplete data on the exact locations exposed to extreme events and the inaccurate (or lack of) damage estimate. A summary of the impact data used can be found in *Table 4*.

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The damage data associated to the reported events were used to calibrate damage functions which correlate the reported loss with the return period of the event and the value of total construction of the area where the event caused impacts. In this study, information on the value of total construction stock was obtained from EUROSTAT[6]. Total construction was used as a proxy of exposure, as damage from wind is typically dominated by infrastructure damage. Projections of the total construction stock are not available. Given that it shows a strong correlation with GDP, future total construction values were obtained by scaling baseline values with the projected changes in GDP based on the ECFIN 2015 Ageing Report (EC, 2015). For the human impact (mortality) we derived mortality rates from the total number of fatalities reported per country over the period 1981-2016 and the number of people exposed to windstorms (corresponding to a 50-year intensity or more severe). Population projections are also according to the 2015 Ageing Report. The national scale socioeconomic data were further downscaled by the LUISA Territorial Platform[7].

The methodological approach to estimate future windstorm impacts can be summarized as follows:

- For each storm event in NatCatSERVICE, we collected the damage, fatalities, location, and date;
- Search for the highest wind speed in a temporal (2-weeks) and spatial (circle with radius of 100 km) window around the date and the location of the reported event;
- Consider only pixels in the search radius with return periods above 5 years and sum the total construction stock corresponding to those pixels;
- Calibrate the damage function/mortality rate using all the reported events with impacts in NatCatSERVICE.

The final damage function (Eq. 1) is a power-based function with the loss (expressed in million euros) as dependent variable and the return period (RP) and the total construction (TC) of the area as independent variables.

$$Loss = TC^{\alpha} RP^{\beta} \qquad \text{(Eq. 1)}$$

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[5] https://natcatservice.munichre.com/

[6] http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nama_10_nfa_fl&lang=en

[7] https://ec.europa.eu/jrc/en/luisa

Optimized parameters α and β equal respectively 0.68 and 0.2 and the overall coefficient of determination (R^2) of the function is 0.42. A comparison between modelled and observed losses is shown in Figure 7.

Table 4. Summary of windstorms reported in Munich RE's NatCatSERVICE disaster database. Fat is for fatalities and dam for damage. The events refer to the period 1981-2016 and the damage is expressed in 2015 €billion.

	events			human	economy
Country	**nr reported events**	**nr events with fat > 0**	**nr events with dam > 0**	**reported fatalities**	**reported damage in billion € (2015)**
Austria	150	23	44	45	3.0
Belgium	66	21	26	55	3.5
Bulgaria	28	11	5	18	0.1
Cyprus	7	1	0	1	0.0
Croatia	17	3	1	3	0.0
Czechia	33	12	5	18	0.4
Denmark	32	9	18	38	7.2
Estonia	9	0	1	0	0.1
Finland	24	2	13	4	0.5
France	194	85	41	470	29.5
Germany	500	160	268	465	44.1
Greece	48	21	4	66	0.7
Hungary	9	4	8	20	0.1
Ireland	55	15	13	54	0.8
Italy	124	61	23	221	2.3
Latvia	14	5	2	10	0.3
Lithuania	8	3	2	9	0.1
Luxembourg	11	0	8	0	0.6
Malta	10	3	1	7	0.0
Netherlands	56	20	24	57	4.0
Poland	64	34	7	112	0.3
Portugal	45	18	12	68	0.6
Romania	35	15	3	97	0.1
Slovakia	15	6	3	14	0.4
Slovenia	9	1	3	1	0.1
Spain	143	73	24	411	5.5
Sweden	49	8	19	35	3.4
United Kingdom	240	115	84	556	23.5
EU and UK	1995	729	662	2854	131

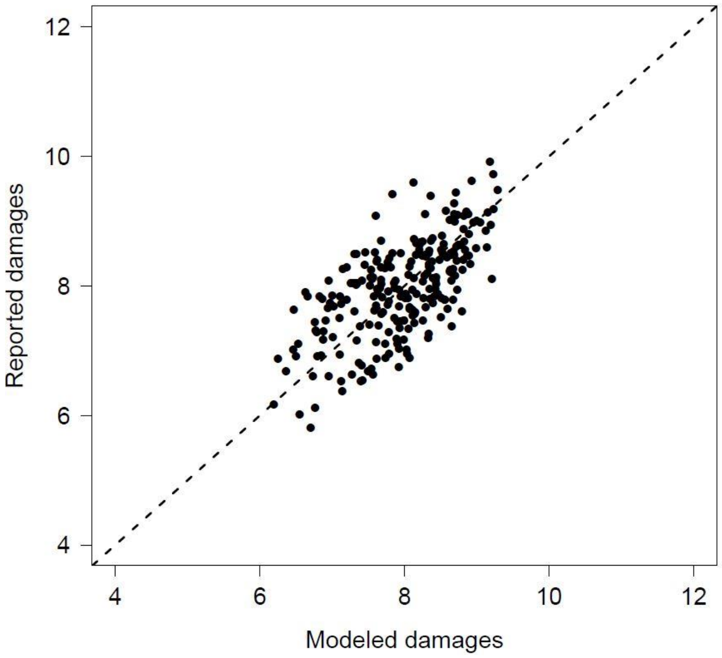

Figure 7. Scatter plot of reported and modelled damage.

A1.5 Impact modelling

The wind risk assessment is based on the combination of the hazard, exposure and vulnerability. For the baseline (1981-2010) and 30-year time windows around the warming levels, the pixel-median wind return period was derived. Using the damage function and mortality rates, the return periods were combined with the layers of total construction and population to obtain the corresponding economic loss, people exposed and number of fatalities. The country expected annual damage, expected annual population exposed and fatalities for the baseline and at the global warming levels was obtained by summing the values over all grid cells in each country.

Annex 2. Additional results

Table 5. Macro-regional percentages of the area for which the projected 10- and 100-year daily maximum wind speed is smaller (-) or larger (+) at a global warming level period compared to the baseline period (1981-2010). No change (=) means that the median change is below 0.3 m/s. If at least two thirds of the simulations agree on the sign of change, it is considered robust (r). CW is for central-western, N for northern, E for eastern, and S for southern Europe.

Indicator		**10-year event**			**100-year event**		
Reg/Period		1.5°C	2°C	3°C	1.5°C	2°C	3°C
N EU	+r	**2.2**	**3.4**	**9.1**	**2.5**	**3.1**	**10.4**
	+	24.0	24.8	25.6	30.7	31.6	31.2
	=	40.0	36.1	27.7	30.7	27.9	18.5
	-	23.9	22.0	22.1	27.9	25.3	26.1
	-r	**9.9**	**13.7**	**15.5**	**8.2**	**12.0**	**13.8**
CW EU	+r	**2.0**	**2.1**	**3.0**	**2.0**	**2.3**	**4.4**
	+	25.6	29.2	23.6	26.6	29.8	25.9
	=	44.3	42.1	28.2	30.9	29.7	16.9
	-	22.4	18.1	25.1	32.4	26.6	28.5
	-r	**5.7**	**8.5**	**20.0**	**8.0**	**11.6**	**24.3**
E EU	+r	**1.6**	**1.4**	**4.3**	**2.0**	**1.8**	**8.6**
	+	19.7	20.8	21.8	28.1	29.2	28.0
	=	50.5	49.2	35.8	34.9	34.6	21.1
	-	16.6	16.9	19.1	23.3	23.1	25.5
	-r	**11.6**	**11.7**	**19.0**	**11.8**	**11.3**	**16.7**
S EU	+r	**11.4**	**7.2**	**12.8**	**12.5**	**7.7**	**16.7**
	+	25.5	23.1	20.5	33.0	32.6	28.3
	=	39.3	38.8	27.9	27.7	27.6	17.1
	-	20.3	22.7	25.1	23.1	24.3	25.6
	-r	**3.6**	**8.2**	**13.8**	**3.7**	**7.8**	**12.3**
EUROPE	+r	**3.9**	**3.0**	**6.4**	**4.3**	**3.2**	**9.6**
	+	23.0	23.4	22.4	29.8	30.4	28.4
	=	44.7	42.6	30.9	31.4	30.4	18.8
	-	20.3	20.6	22.9	26.1	25.6	27.1
	-r	**8.1**	**10.4**	**17.3**	**8.4**	**10.3**	**16.2**

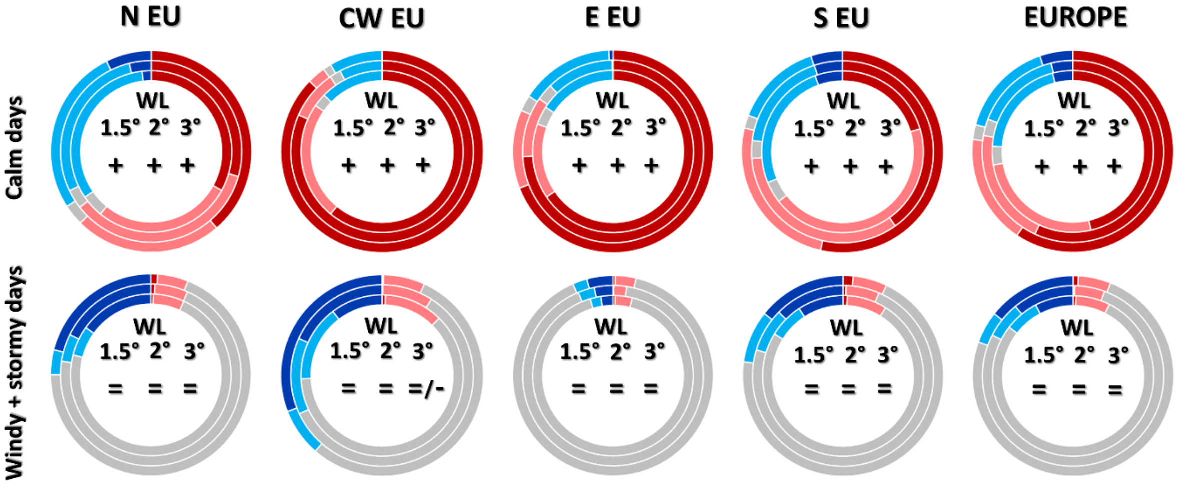

Figure 8. Macro-regional changes compared to baseline in the total number of calm days (daily maximum wind speed <3.4 m/s) and windy/stormy days (daily maximum wind speed >20.7) for different warming levels. Shown are percentages of the area with changes in calm and stormy days that are negligible (ensemble median change <5 days, grey), not negligible but not robust (ensemble median change >5 days but <2/3 of models agree on sign of change, pink and light blue), and robust (change >5 days and ≥2/3 models agree on sign of change, dark red and blue). Inner (outer) circle represents 1.5°C (3°C) warming.

Table 6. Projected ensemble median Expected Annual Damage (EAD, expressed in % relative to the GDP) for baseline (1981-2010) and warming levels for the alternative economic scenarios.

	Base society				2050 society		2100 society		
Country	**base**	**1.5°C**	**2.0°C**	**3.0°C**	**1.5°C**	**2.0°C**	**1.5°C**	**2.0°C**	**3.0°C**
Austria	0.04	0.04	0.05	0.04	0.04	0.04	0.03	0.03	0.03
Belgium	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02
Bulgaria	0.08	0.08	0.07	0.09	0.06	0.05	0.05	0.05	0.06
Cyprus	0.04	0.04	0.04	0.03	0.04	0.04	0.03	0.03	0.03
Croatia	0.07	0.06	0.07	0.08	0.05	0.06	0.04	0.05	0.06
Czechia	0.06	0.05	0.05	0.06	0.04	0.04	0.03	0.03	0.04
Denmark	0.04	0.03	0.04	0.03	0.03	0.03	0.02	0.03	0.02
Estonia	0.08	0.07	0.06	0.05	0.06	0.05	0.05	0.04	0.04
Finland	0.06	0.06	0.06	0.06	0.05	0.05	0.04	0.04	0.04
France	0.03	0.04	0.04	0.04	0.03	0.03	0.02	0.02	0.03
Germany	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.03
Greece	0.04	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02
Hungary	0.06	0.06	0.07	0.08	0.05	0.05	0.04	0.04	0.05
Ireland	0.05	0.05	0.05	0.04	0.04	0.04	0.03	0.03	0.02
Italy	0.04	0.03	0.03	0.04	0.03	0.03	0.03	0.03	0.03
Latvia	0.07	0.06	0.06	0.06	0.05	0.05	0.04	0.04	0.04
Lithuania	0.07	0.07	0.07	0.06	0.05	0.06	0.04	0.05	0.04
Luxembourg	0.04	0.03	0.04	0.04	0.02	0.03	0.02	0.02	0.02
Malta	0.04	0.06	0.05	0.03	0.07	0.06	0.06	0.05	0.03
Netherlands	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02
Poland	0.06	0.05	0.06	0.05	0.04	0.04	0.04	0.04	0.04
Portugal	0.03	0.04	0.03	0.04	0.04	0.03	0.03	0.03	0.03
Romania	0.06	0.07	0.07	0.08	0.05	0.05	0.04	0.04	0.05
Slovakia	0.06	0.06	0.06	0.08	0.05	0.05	0.04	0.04	0.05
Slovenia	0.07	0.07	0.07	0.08	0.06	0.06	0.05	0.05	0.05
Spain	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.03
Sweden	0.05	0.05	0.05	0.05	0.04	0.04	0.03	0.03	0.03
United Kingdom	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02
EU and UK	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03

Table 7. Projected ensemble median Expected Annual Fatalities (EAF) for baseline (1981-2010) and warming levels for the alternative economic scenarios.

	Base economy				Economy 2050		Economy 2100		
Country	**base**	**1.5°C**	**2.0°C**	**3.0°C**	**1.5°C**	**2.0°C**	**1.5°C**	**2.0°C**	**3.0°C**
Austria	1	1	1	1	1	1	1	1	1
Belgium	1	1	1	1	2	2	2	2	2
Bulgaria	0	0	0	1	0	0	0	0	0
Cyprus	0	0	0	0	0	0	0	0	0
Croatia	0	0	0	0	0	0	0	0	0
Czechia	0	0	0	0	0	1	0	0	0
Denmark	1	1	1	1	1	1	1	1	1
Estonia	0	0	0	0	0	0	0	0	0
Finland	0	0	0	0	0	0	0	0	0
France	13	13	12	12	15	14	16	15	15
Germany	13	12	12	12	11	11	10	10	9
Greece	2	2	2	2	1	1	1	1	1
Hungary	1	1	1	1	1	1	0	0	1
Ireland	1	2	1	1	2	2	2	2	2
Italy	6	6	6	6	7	6	6	6	6
Latvia	0	0	0	0	0	0	0	0	0
Lithuania	0	0	0	0	0	0	0	0	0
Luxembourg	0	0	0	0	0	0	0	0	0
Malta	0	0	0	0	0	0	0	0	0
Netherlands	2	1	1	1	2	2	2	2	1
Poland	3	3	3	3	3	3	2	2	2
Portugal	2	2	2	1	2	1	1	1	1
Romania	3	3	3	3	2	2	2	2	2
Slovakia	0	0	0	0	0	0	0	0	0
Slovenia	0	0	0	0	0	0	0	0	0
Spain	11	12	10	10	11	10	10	9	8
Sweden	1	1	1	1	1	1	1	1	1
United Kingdom	15	16	16	15	19	19	21	21	20
EU and UK	77	78	75	74	80	79	76	74	73

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List of abbreviations and definitions

CMIP – Coupled Model Intercomparison Project

CORDEX – Coordinated regional Climate Downscaling Experiment

EAD – Expected Annual Damage

EAF – Expected Annual Fatalities

EAPE – Expected Annual Population Exposed

EC – European Commission

ECFIN – European Commission for Economic and Financial Affairs

ECMWF – European Centre for Medium range Weather Forecasting

EEA – European Environmental Agency

EMS – European Monitoring System

ERA – European Reanalysis

EU – European Union

EVA – Extreme Value Analysis

GCM – General Climate Model

GDP – Gross Domestic Product

LUISA – Land Use Integrated Sustainability Assessment platform

Munich RE – Munich Reinsurance

NatCatSERVICE – Natural Catastrophe Statistics Online Service Analysis Tool of Munich RE

PESETA – Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis

RCM – Regional Climate Model

RCP – Representative Concentration Pathway

RL –Return Level

RP – Return Period

GWL – Global Warming Level

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