Increasing risk over time of weather-related hazards to the European population: a data-driven prognostic study

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Summary

Background **The observed increase in the effects on human beings of weather-related disasters has been largely attributed to the rise in population exposed, with a possible influence of global warming. Yet, future risks of weather-related hazards on human lives in view of climate and demographic changes have not been comprehensively investigated.**

Methods **We assessed the risk of weather-related hazards to the European population in terms of annual numbers of deaths in 30 year intervals relative to the reference period (1981–2010) up to the year 2100 (2011–40, 2041–70, and 2071–100) by combining disaster records with high-resolution hazard and demographic projections in a prognostic modelling framework. We focused on the hazards with the greatest impacts—heatwaves and cold waves, wildfires, droughts, river and coastal floods, and windstorms—and evaluated their spatial and temporal variations in intensity and frequency under a business-as-usual scenario of greenhouse gas emissions. We modelled long-term demographic dynamics through a territorial modelling platform to represent the evolution of human exposure under a corresponding middle-of-the-road socioeconomic scenario. We appraised human vulnerability to weather extremes on the basis of more than 2300 records collected from disaster databases during the reference period and assumed it to be static under a scenario of no adaptation.**

Findings **We found that weather-related disasters could affect about two-thirds of the European population annually by the year 2100 (351 million people exposed per year [uncertainty range 126 million to 523 million] during the period 2071–100) compared with 5% during the reference period (1981–2010; 25 million people exposed per year). About 50 times the number of fatalities occurring annually during the reference period (3000 deaths) could occur by the year 2100 (152 000 deaths [80 500–239 800]). Future effects show a prominent latitudinal gradient, increasing towards southern Europe, where the premature mortality rate due to weather extremes (about 700 annual fatalities per million inhabitants [482–957] during the period 2071–100 *vs* 11 during the reference period) could become the greatest environmental risk factor. The projected changes are dominated by global warming (accounting for more than 90% of the rise in risk to human beings), mainly through a rise in the frequency of heatwaves (about 2700 heat-related fatalities per year during the reference period *vs* 151 500 [80 100–239 000] during the period 2071–100).**

Interpretation **Global warming could result in rapidly rising costs of weather-related hazards to human beings in Europe unless adequate adaptation measures are taken. Our results could aid in prioritisation of regional investments to address the unequal burden of effects on human beings of weather-related hazards and differences in adaptation capacities.**

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Introduction

Climate change is one of the biggest global threats to human health of the 21st century.[1] Its peril to society will be increasingly connected to weather-driven hazards[2–4] because extreme weather states are expected to disproportionately rise compared with changes in climate averages.[5] Human beings are affected by extreme weather events through a set of complex pathways, including direct effects, such as death and immediate injuries when the event strikes a society, and delayed or indirect effects, such as illness, mental health effects, and effects associated with the ecology of infectious diseases and disruption of crucial infrastructure.[1,6] Demographic growth and shifts to hazard-prone locations, such as coastal zones and cities, can increase the number of human beings exposed and ultimately lead to increased risk.[7,8] In view of these pressures, the future effects of weather-related extremes on people need to be quantified to identify where and to what extent their livelihoods will be at risk in the future and develop timely and effective adaptation and disaster risk reduction strategies.

Human risks arise from interactions of the hazards, the societies exposed to the hazards, and the vulnerability of the societies to adverse effects when exposed. Disentangling of the contributions of these drivers is a complex process because of little understanding of population vulnerability and the absence of well established

Research in context

Evidence before this study

We searched PubMed and Scopus for articles published up to July 5, 2017, with no language restrictions, using the search terms "forecasting" OR "projection" OR "estimation" OR "prediction", "weather" OR "climate", "hazard" OR "risk" OR "impact", and "human" OR "health" OR "population" OR "people" in the publication title and abstract. The identified studies on the effect of weather-related extremes on human beings have mainly targeted the effects of heat-related mortality, often focusing on specific settings, such as urban areas. Few studies document regional-to-global-scale effects. For most other weather-related hazards, estimation of effects on human beings is hampered by the absence of observation-based vulnerability relations. Furthermore, other drivers of risk, such as demographic changes, are often not considered in hazard effect assessments.

Added value of this study

Our study provides a comprehensive assessment of weather-driven single-hazard and multihazard effects on the European population until the year 2100 under a scenario of no adaptation. For this purpose, we developed a novel method that combines weather-related disaster records with a set of high-resolution projections of climate hazard and population density. Expected effects on populations are quantified in terms of number of people exposed and fatalities. We consistently assessed how the seven most harmful weather-related extremes (heatwaves and cold waves, droughts, wildfires, river and coastal floods, and windstorms) might evolve in Europe in view of global warming. Previous assessments of the effects on human beings of climate extremes focused mostly on the effects of temperatures. We derived population vulnerability to each hazard on the basis of an exhaustive dataset of observed weather-related disaster losses collected from multiple disaster databases. We incorporated high-resolution demographic dynamics in our modelling framework to account for variations in human exposure as another key driver of change in human risk. Existing studies are typically restricted to the effects on today's population or, at best, use national projections. Integration of these elements provides plausible estimates of extreme weather-related risks on future European generations.

Implications of all the available evidence

This study contributes to the ongoing debate about the need to urgently curb climate change and minimise its unavoidable consequences, as emphasised by the Paris Agreement built on the UN Framework Convention on Climate Change. Our findings shed light on the expected burden of climate on societies across different regions of Europe. The substantial rise in risk of weather-related hazards to human beings due to global warming, population growth, and urbanisation highlights the need for stringent climate mitigation policies and appropriate adaptation and risk reduction measures to minimise the future effect of weather-related extremes on human lives. In that respect, our results are particularly relevant for the first priority action "understanding disaster risk" of the UN Sendai Framework for Disaster Risk Reduction and objective two "promoting better informed decision-making by addressing gaps in knowledge" of the European Union Strategy on Adaptation to Climate Change.

scientific methods.[9,10] Several studies[11,12] have derived analytical functions that relate mortality to extreme temperatures under today's climate and extrapolated them to climate change scenarios. Relationships differ by climate zone, geographical area, and temperature metrics,[13] and only a few studies[10,14–16] document regional-scale-to-global-scale effects. Future effects of river and coastal floods have also been extensively studied.[17,18] However, these approaches generally neglect human vulnerability and only report the population potentially exposed (eg, people living within the flooded areas), without expressing the corresponding proportion of potential fatalities in the population.[19] For most other weather-related hazards, estimation of human effects is hampered by an absence of robust vulnerability models based on observation-driven statistics. Difficulties in establishment of comparisons of hazards remain particularly relevant, and no comprehensive projections of the effects of weather-related extremes on human beings in Europe have yet been provided.

To make progress on these issues, we present a detailed assessment of the evolution of single-hazard and multihazard risks for the population of Europe until the year 2100. We quantify the human effects as a multiplicative function of hazard, exposure, and population vulnerability. Integration of these three elements provides future estimates of plausible human risks, which are strongly rooted in the observational records and account for the combined effects of climate and population changes.

Methods

Methodological framework

We used the risk framework proposed by the Intergovernmental Panel on Climate Change[20] to estimate the people exposed (R_{exp}) as a combination of hazards (H; weather-related extremes) and exposure (E; population distribution)—ie, $R_{exp}=H\times E$. The effect on human beings is ultimately expressed in terms of deaths (R_{fat}) as a function of hazards, exposure, and population vulnerability (V)—ie, $R_{fat}=H\times E\times V$. Each of these risk components is described in the following sections. Weather-related risks are expressed as relative variations compared with the reference period (1981–2010) and were derived for the following 30 year time intervals: 2011–40, 2041–70, and 2071–100. Analyses are done at the spatial resolution of 1 km for the 28 European Union (EU) countries as well as

Switzerland, Norway, and Iceland (EU+). We used MATLAB R2012 for statistical analyses. Details of the general methods are reported in the appendix.

Hazards (weather-related extremes)

We derived weather-related hazard indicators for heatwaves and cold waves, river and coastal floods, streamflow droughts, wildfires, and windstorms for the reference period and future time periods for an ensemble of climate projections under the business-as-usual SRES A1B greenhouse gas emissions scenario (appendix). The hazard term (H) is expressed as the fraction of the territory that is expected to be exposed annually to a hazard with the intensity of a present 100 year event or more intense. We calculated it by integrating the territory subject to hazard intensities over the probability of occurrence distribution of hazard intensities retrieved through extreme value analysis. For pixels with non-significant changes, we kept baseline H values for future time periods. This approach implies that the projections of effects reported in this study only reflect significant changes (p value of <0·05) in weather-driven hazards due to climate change. Details are reported in the appendix.

Exposure (population distribution)

We assessed changes in population exposure (E) consistent with the middle-of-the-road Shared Socio-economic Pathway and business-as-usual climate scenario (SRES A1B)[21] for the reference period and future time periods by generating high-resolution projections of gridded population density for Europe with the Land Use-based Integrated Sustainability Assessment territorial modelling platform.[22] These maps capture the fine-scale processes of population dynamics (eg, urban expansion, stagnation or degrowth, and concentration) that represent key drivers of the future exposure of populations. We derived complementary information on the degree of urbanisation of municipalities from the Eurostat dataset[23] and the share of elderly people (>65 years of age) in future societies from the European Commission dataset.[24] Details are reported in the appendix.

Population vulnerability

Vulnerability (V) describes the relationship between the exposure to a weather-related hazard and the effect on human beings. It is quantified in this study as the ratio between the people killed by a climate disaster (R_{fat}) and the population exposed to the hazard with intensity (or frequency) equal to or larger (lower) than the current 100 year event (R_{exp}). To appraise V for the reference period, we calculated R_{exp} over the period 1981–2010. We obtained R_{fat}, expressed as the annual number of deaths for each hazard and country, from more than 2300 weather-related disaster records collected over the same period in the Emergency Events Database and Munich Re's NatCatSERVICE[25] disaster database. We quantified vulnerability at country level and considered it to be static with time, thus assuming no changes in human vulnerability or additional measures to enhance human capacity to cope with future extreme climate conditions. Details are reported in the appendix.

See Online for appendix

Effects on human beings of single and multiple weather-related extremes

Future effects on human beings—ie, number of people exposed (R_{exp}) and deaths (R_{fat})—are separately calculated for each hazard and climate realisation to sample the intermodel climate spread. The overall effect of weather-related hazards is calculated as the sum of the multimodel medians of the effects of each single hazard and the corresponding uncertainty, expressed as the multimodel maximum and minimum of the effects of each single hazard. We implicitly assume that the single-hazard effects are independent (appendix). Spatial maps of effects for the reference period and future time periods are obtained by downscaling country effects to Nomenclature of Statistical Territorial Units 2 level according to the spatial distribution of the exposed population. Details are reported in the appendix. Estimates of weather-related effects for the reference period and future time periods are fully conditional on the recorded losses. Hence, any deviations of the reported deaths from the true effects are inherently translated into future losses.

Role of the funding source

The funder had no role in study design, data collection, data analysis, data interpretation, or writing of the report. All authors had full access to all the data in the study and the corresponding author had final responsibility for the decision to submit for publication.

Results

Our projections show a rapid rise in the death toll due to weather-related disasters in Europe during this century under a scenario of climate and population change (figure 1). During the reference period (1981–2010), around 3000 Europeans lose their lives each year because of weather disasters. If no adaptation measures are implemented, this number could rise substantially in the coming decades, to reach 32 500 deaths (uncertainty range 10 700–59 300) by the period 2011–40 (about a ten-times increase), 103 300 (48 300–179 300) by 2041–70 (about a 30-times increase), and 152 000 (80 500–239 800) by 2071–100 (about a 50-times increase). The population that is exposed on an annual basis is projected to increase from 25 million per year during the reference period to 78 million (27 million to 166 million) by the period 2011–40, 236 million (74 million to 471 million) by 2041–70, and 351 million (126 million to 523 million) by 2071–100. These findings imply that, by the end of this century, about two-thirds of Europeans could be exposed to a weather-related disaster every year compared with 5% during the reference period.

For the **Emergency Events Database** see http://www.emdat.be

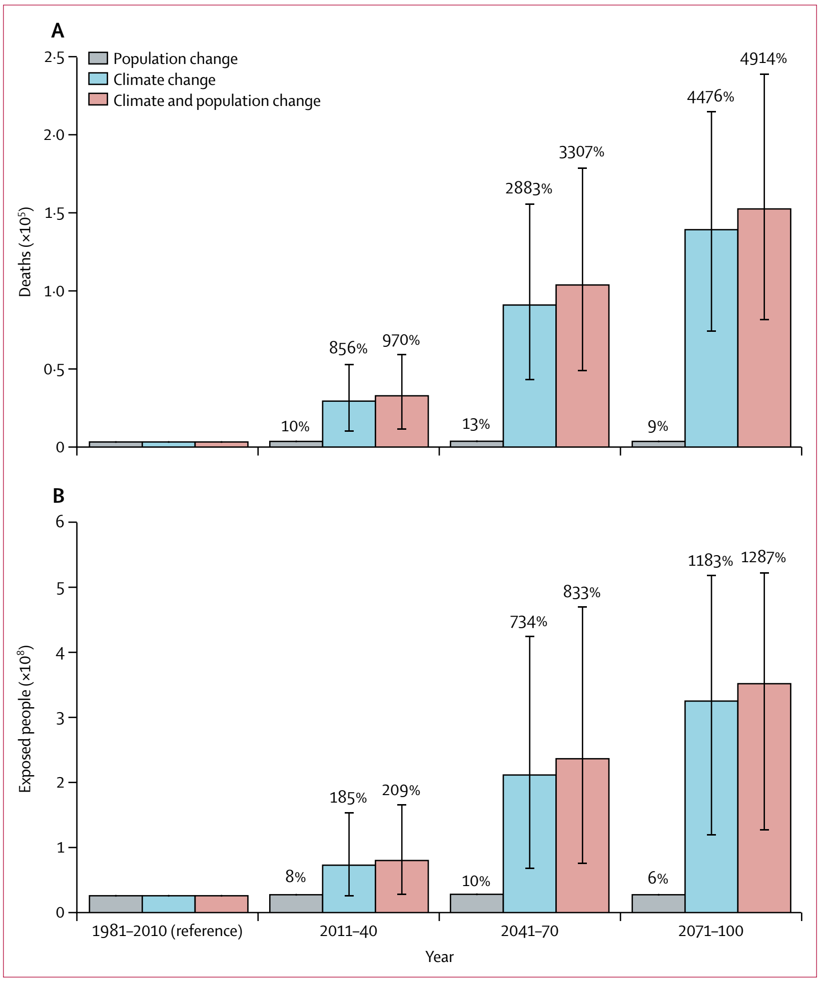

Figure 1: **Overall risk of weather-related hazards to the European population for each time period**
Number of deaths due to (A) and number of people exposed to (B) multiple weather-related hazards under different scenarios. Error bars represent the intermodel climate variability (uncertainty range) and percentages report the relative variations with respect to the reference period.

Climate change is the dominant driver of the projected trends, accounting for more than 90% of the rise in the risk to human beings (figure 1). This finding is because Europe is expected to face major changes in the frequency of multiple climate extremes during the coming decades (appendix) and be exposed to a progressive and strong increase in overall weather-related hazards. In particular, very rare (and often high-impact) extreme events are expected to increase in frequency more than high-probability low-effect weather-related hazards.[26]

The effects of hazards on human lives differ greatly in terms of both magnitude and rate of change (figure 2). Heatwaves are the most lethal weather-related hazard. During the reference period, about 2700 heat-related fatalities per year were reported in Europe by the disaster databases. This number is projected to grow exponentially, to reach 151 500 (uncertainty range 80 100–239 000) by the period 2071–100 (5400% relative increase), or 99% of the total future weather-related disaster death toll. These numbers are within the range reported in previous pan-European epidemiological studies.[14,15] Fatalities associated with coastal flooding also rise substantially (by 3780%), leading to 233 deaths every year during 2071–100 compared with only six fatalities per annum during the reference period. The increase in deaths caused by wildfires (138%) is expected to claim about 57 lives every year by 2071–100 (15–136), the increase caused by river floods (54%) is expected to claim about 106 (60–239), and the increase caused by windstorms (20%) is predicted to claim about 124 (111–161). Droughts can be lethal in low-income and middle-income countries, mostly because of poor agricultural techniques and under-nutrition.[27] On the contrary, people in high-income countries have diverse diets (based on food from geographically diffuse producers) and guaranteed access to clean water for basic needs.[28] Therefore, fatalities from droughts are rare in Europe and have not been reported in the observational period of this study. As a positive consequence of global warming, the number of fatalities from cold waves will decline strongly. However, this effect will not be sufficient to compensate for the above-mentioned rise in fatalities from other hazards.

The striking growth in weather-related fatalities projected in this study reflects the increase of the European population exposed to intense hazards, which will probably result in an increase in other, non-lethal effects on human beings (appendix). Direct injuries from flooding, windstorms, and wildfires could rise in the areas hit by the hazard. Because of more frequent and intense droughts (a longer lasting and spatially dispersed hazard) in the future than at present, the number of people faced with reduced water resources for food production, domestic use, and other basic needs for human wellbeing could grow to 138 million people (uncertainty range 32 million to 322 million) per year by 2071–100, or more than 27 times the number during the reference period (5 million). With 211 million Europeans (83 million to 379 million) annually exposed to heatwaves by 2071–100—compared with the 5 million during the reference period (figure 2)—cardiovascular, cerebrovascular, and respiratory diseases might amplify. Furthermore, mental health disorders associated with weather-related disasters, such as post-traumatic stress disorder and depression,[29] could also increase.

The overall progressive increased risk to human beings shows a prominent latitudinal gradient towards southern European countries (figure 3). This pattern is largely driven by the stronger rise in the frequency and intensity of heatwaves towards the south, fewer droughts in northern Europe, and an upsurge in drought conditions in southern regions (appendix). By 2071–100, about a third of the population in northern Europe and almost all of those in southern Europe could be exposed to a weather-related hazard annually (table). In southern Europe, this figure might result in about 700 (482–957 uncertainty range) annual fatalities from weather extremes per million inhabitants by 2071–100 compared with 11 during the reference period. This figure exceeds the premature mortality rate due to air pollution in Europe in 2010 (439 annual deaths per million people) and by 2050 (598 annual deaths per million people),[30] which is considered the greatest environmental risk factor for disease burden in Europe today.[31]

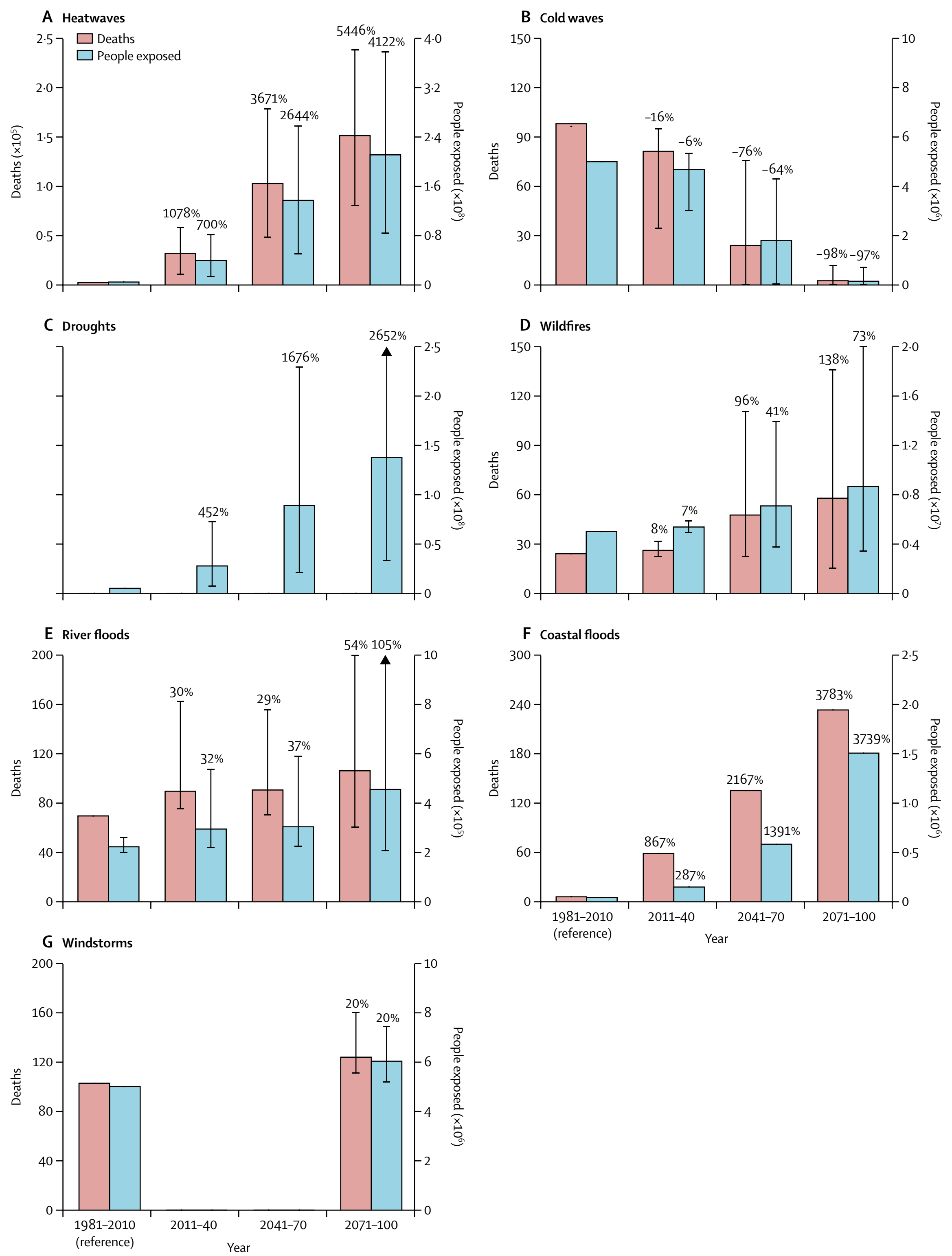

Figure 2: **Effect of individual weather-related hazards on the European population**
Error bars represent the intermodel climate variability (uncertainty range) and percentages report the relative variations with respect to the reference period. The effects of coastal floods have been produced for one climate configuration and the effects of windstorms have been produced only for the reference period and 2071–100 (appendix). For droughts, only non-fatal events have been recorded in disaster databases, thus only projections of people exposed are provided (appendix).

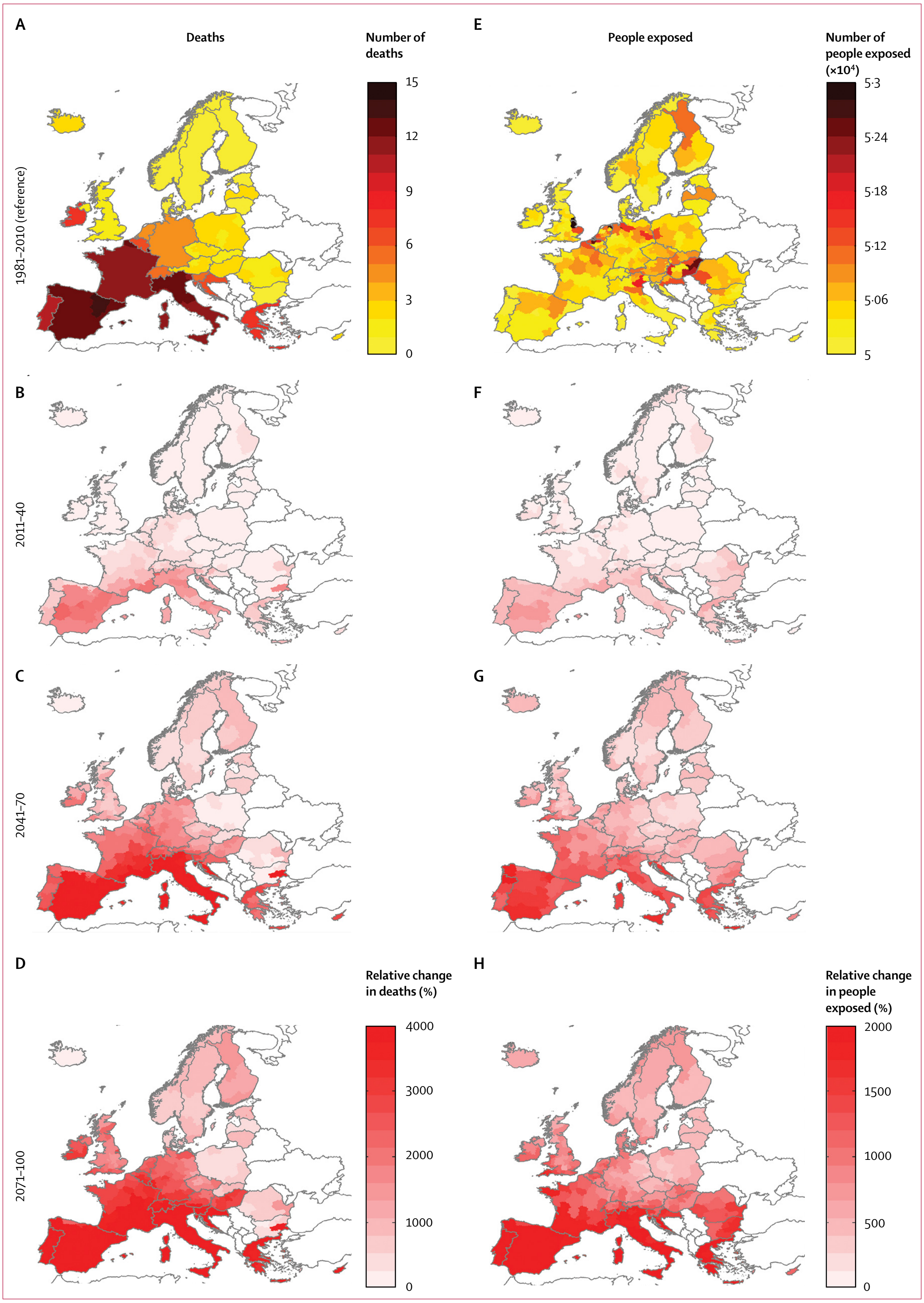

***Figure 3:* Spatial and temporal patterns of projected changes in the overall risk of weather-related hazards**
Number of deaths (A) and people exposed (E) per year aggregated at the Nomenclature of Statistical Territorial Units 2 level due to multiple weather-related hazards recorded during the reference period per 1 million inhabitants. Corresponding simulated changes of deaths for 2011–40 (B), 2041–70 (C), and 2071–100 (D), and of people exposed for 2011–40 (F), 2041–70 (G), and 2071–100 (H), under climate and population change scenarios.

	Northern Europe		Eastern Europe		Central Europe		Western Europe		Southern Europe	
	1981–2010	2071–100	1981–2010	2071–100	1981–2010	2071–100	1981–2010	2071–100	1981–2010	2071–100
Deaths (per 10 million inhabitants)										
Heatwaves	0·98	27·24 (3·1–60·61)	4·81	177·46 (49·48–316·68)	61·51	2305·77 (729·63–4547·2)	34·33	1022·67 (126·27–1694·07)	105·77	7019·99 (4813·5–9555·39)
Cold waves	0·2	0	8·82	0·34 (0–1·63)	0·36	0 (0–0·02)	0·66	0·03 (0–0·16)	0·33	0·01 (0–0·04)
Droughts	0	0	0	0	0	0	0	0	0	0
Wildfires	0·26	0·33 (0·23–0·59)	0·26	0·33 (0·14–0·7)	0·12	0·13 (0·04–0·32)	0·38	0·63 (0·25–1·79)	1·4	3·45 (1·02–8·25)
River floods	0·33	0·51 (0·2–1·29)	2·65	3·28 (2·39–6·95)	0·52	1·27 (0·49–3·85)	0·97	2·08 (1·08–4·6)	2·22	2·93 (1·99–5·1)
Coastal floods	0·07	1·43 (1·43–1·43)	0·35	10·86 (10·86–10·86)	0·18	6·64 (6·64–6·64)	0·08	0·97 (0·97–0·97)	0·02	1·14 (1·14–1·14)
Windstorms	1·46	1·84 (1·5–2·45)	1·46	1·54 (1·25–2·08)	2·62	3·09 (2·71–3·88)	1·85	2·17 (1·84–2·51)	1·93	2·16 (1·88–2·5)
Overall	3·3	31·34 (6·46–66·37)	18·34	193·8 (64·12–338·89)	65·32	2316·91 (739·51–4561·91)	38·27	1028·56 (130·41–1704·1)	111·68	7029·69 (4819·53–9572·42)
People exposed (per 1 million inhabitants)										
Heatwaves	9618	269 167 (30 725–605 027)	9989	341 025 (94 012–621 254)	9932	322 309 (77 923–736 902)	9993	298 558 (38 256–495 932)	9828	634 474 (429 199–878 633)
Cold waves	9618	3 (0–9)	9989	622 (0–3059)	9932	143 (0–606)	9993	456 (0–2280)	9828	331 (0–1503)
Droughts	9618	63e206 961 (1461–346 239)	9989	91 901 (3744–370 377)	9932	289 207 (38 637–710 174)	9993	121 557 (4115–505 631)	9828	437 632 (179 724–673 001)
Wildfires	9618	12 322 (8515–21 981)	9989	15 950 (6683–33 902)	9932	13 743 (5311–30 840)	9993	18 157 (7425–51 347)	9828	19 432 (6016–42 681)
River floods	243	347 (148–740)	644	822 (588–1578)	420	1134 (391–4023)	516	1036 (502–2436)	296	402 (239–823)
Coastal floods	68	1572 (1572–1572)	6	115 (115–115)	178	5849 (5849–5849)	20	248 (248–248)	61	1554 (1554–1554)
Windstorms	9618	11 730 (9463–15 270)	9989	12 004 (9448–17 887)	9932	11 365 (10 010–14 217)	9993	11 530 (9654–13 442)	9828	10 199 (9038–11 436)
Overall	48 403	359 102 (51 884–871 809)	50 595	462 439 (114 591–872 621)	50 260	643 750 (138 122–1 000 000)	50 503	451 542 (60 200–982 453)	49 497	990 168 (625 769–999 572)

Data in parentheses are uncertainty ranges. Uncertainty ranges represent the intermodel climate variability. European regions, results for the 2011–40 and 2041–70 time periods and for Europe as a whole, and effects in absolute terms listed by country and Europe as a whole are reported in the appendix.

***Table:* Weather-related risk by region calculated for the reference period and the period 2071–100**

Demographic trends, such as population growth, migration, and urbanisation, are among the most important drivers of disaster risk in the past.[32] For the future, our projections show a minor contribution of population growth and distribution to the overall multi-hazard human risk in Europe, peaking during the period 2041–70, with a contribution to rising effects of around 10% (figure 1). For certain hazards, and at local scales, demographic changes can be of greater importance than for Europe as a whole. For example, the mean proportion of people living in coastal flood-prone areas in Europe is expected to increase by 14% more than the total population, with the most notable increases in Slovenia (205%), Ireland (192%), Norway (184%), Portugal (161%), and the UK (148%; appendix). Furthermore, urbanisation is expected to continue—although at slower rates than in recent decades (mean urbanisation increase of 0·4% per year up to 2050 [appendix] compared with 2·5% per year over the 1970–2000 period[33])—leading to roughly 50 million (18%) additional city dwellers in Europe by 2050. This urbanisation will probably amplify heat-induced effects through the urban heat island effect (ie, built-up areas absorb and retain heat and are therefore hotter than natural land cover).[34] The combined effects of heatwaves and air pollution[35] might further exacerbate human stress in densely populated areas. Additionally, urbanisation increasingly concentrates the demand for water[36] and reduces water retention and the infiltration capacity of the land surface,[37] augmenting the risk of water stress and flooding.

Discussion

This study shows that, unless global warming is curbed as a matter of urgency and appropriate adaptation measures are taken, about 350 million Europeans could be exposed to harmful climate extremes on an annual basis by the end of this century, with a 50-times increase in fatalities compared with now. Our results, based on the assumption of static vulnerability to weather-related hazards, could provide a benchmark for the monitoring of future multihazard vulnerability in support of the *Lancet* Countdown[38] to track the effects on health of climate hazards.

Although not specifically addressed in this study, certain social classes could be more distressed by weather-related hazards than others. In particular, the most vulnerable will be elderly people and those with diseases (who have reduced physiological and behavioural capacity for thermoregulation), as well as the poor (who have less access to technological means for private disaster stress mitigation than do rich people—eg, through air conditioning, thermal insulation, or floodproofing of dwellings). Consequently, population ageing in Europe, which emerges as a major demographic trend for the coming decades (appendix), could further increase the effect on human beings of weather-related hazards. Conversely, expected advances in technology and economic growth will have an opposite tendency to reduce vulnerability through improved adaptation measures. The net effect of these socioeconomic processes remains uncertain.

The strengths of our study are that our risk estimates are based on the two most comprehensive disaster databases available and that projections use state-of-the-art methods. The weakness is the inherent uncertainty in the observation data and in the climate and hazard projections. The main limitations of the different parts of the methods are detailed in the appendix.

Notwithstanding the fact that our estimates are subject to uncertainty, they do highlight important trends. Global warming, demographic changes, and urban expansion could result in rapidly rising effects of weather-related hazards on human beings in Europe if no stringent climate mitigation and disaster risk reduction activities are implemented. The projections thus advocate fulfilment of the key goals of the Paris Agreement[39] to limit global warming and increase resilience to climate change to preserve the health and wellbeing of future generations of people in Europe. Land use and city planning can play an important role in achievement of a healthy, carbon-neutral, and resilient society.[40] They offer strategies to curtail energy consumption and greenhouse gas emissions, such as reduction of urban sprawl and automobile dependence, and are, in many instances, the most effective tools for reduction of the number of human beings exposed and their vulnerability to extreme weather events[41] (eg, housing and building acclimatisation). A systematic approach to spatial planning to enhance health and sustainability requires strong cooperation across societal sectors and institutions, which should be supported by far-sighted policy. This approach should be accompanied by awareness campaigns, improved early warning systems, and action plans tailored to elderly people, deprived groups, and other vulnerable groups. The findings of this study could further aid in prioritisation of investments to address the unequal burden of effects of weather-related hazards and differences in adaptation capacities across Europe.

Contributors

GF and LF conceived and designed the study. FBeS provided high-resolution population projections. GF analysed data. GF and LF interpreted results and wrote the manuscript with contributions from FBeS and AC.

Declaration of interests

We declare no competing interests.

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