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Global warming and human impacts of heat and cold extremes in the EU

JRC PESETA IV project – Task 11

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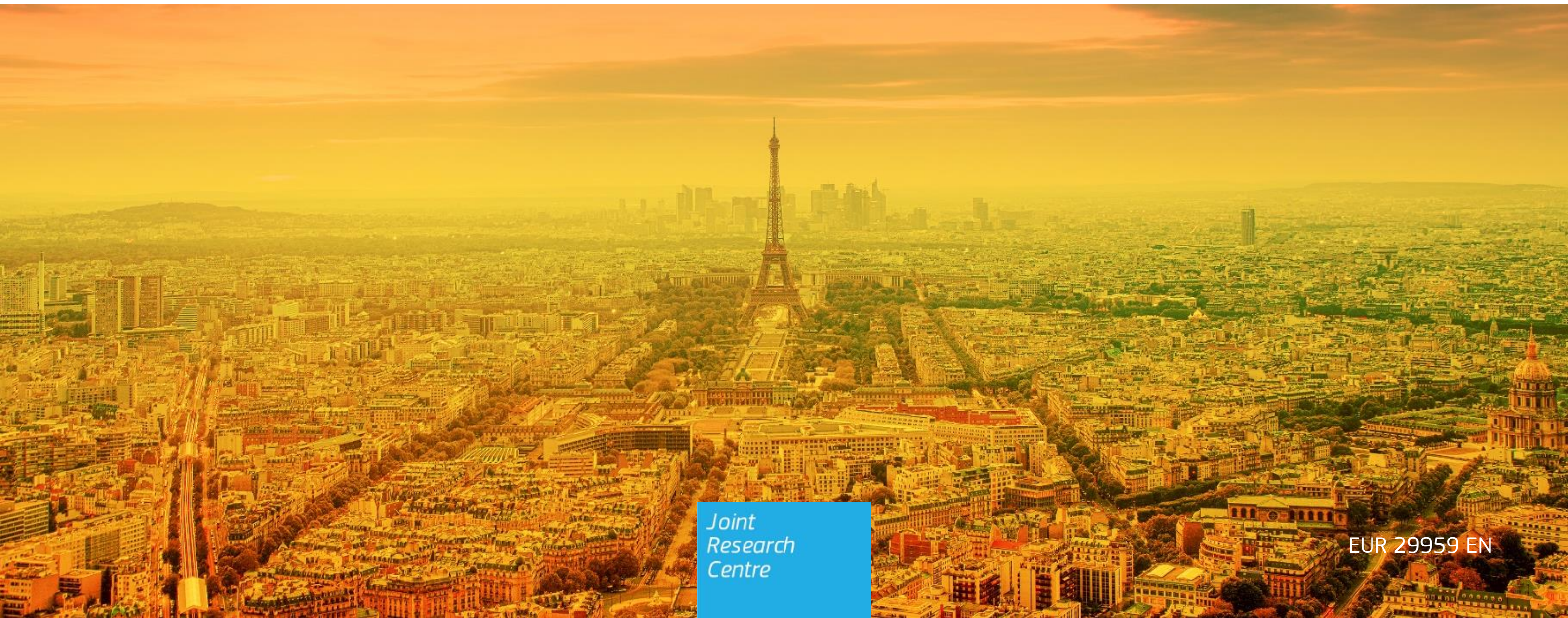

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Executive summary

During intense heatwaves in June and July 2019, all-time temperature records were broken in many locations in Europe. These events are projected to happen more frequently and become more intense with climate change. Projections show that the number of citizens in the EU and UK exposed to heatwaves will grow from 10 million/year (average 1981-2010) to nearly 300 million/year, or more than half the EU population, in a scenario with 3°C global average warming by the end of this century. In case of no adaptation this could result in 96,000 fatalities/year from extreme heat, compared to 2,750 annual deaths at present. Curbing global warming to 1.5°C would limit mortality from extreme heat to around 30,000 fatalities/year. The rise in exposure to and projected fatalities from extreme heat is most pronounced in southern Europe. Milder winters will reduce significantly exposure to and fatalities from extreme cold, nearly 10-fold with 3°C global average warming by the end of this century.

Current effects of heat and cold extremes

Spells of several consecutive days of unusually high or cold temperatures can have considerable impact on people. Since 1980, heat and cold waves have resulted in nearly 90,000 fatalities in Europe. A large majority of the reported fatalities from temperature extremes relate to heatwaves. The more vulnerable are older people and those with diseases who have reduced physiological and behavioural capacity for thermoregulation, as well as the poor who have less means for private extreme temperature mitigation (e.g. through air conditioning or thermal insulation).

Projections of heat and cold extremes with global warming

Global warming will progressively increase the frequency and severity of heatwaves and result in a gradual decline in the intensity and frequency of extreme cold spells. Both trends are very strong across the EU and UK, but are somewhat more pronounced in southern European countries. In a 3°C warmer climate compared to pre-industrial times, a current 50-year heatwave may occur almost every year in Spain and parts of Portugal, every 3 years in most other southern European areas and at least every 5 years in other regions of Europe.

base	1.5˚C	2.0˚C	3.0˚C
People annually exposed to a 50-year heatwave (million)			
9.6	105	172	298
Annual fatalities from heatwaves (x1000)			
2.8	30.3	52.4	96.0

Figure 1. Human exposure to and fatalities from heatwaves in the EU and UK for different warming levels in 2100.

Future impacts of heat and cold extremes

The projected change in heatwave hazard results in a strong rise in the number of people exposed to extreme heat with global warming (Figure 1). Even when temperatures could be stabilized at 1.5°C, by the end of this century each year more than 100 million citizens in the EU and UK are expected to be exposed to a present 50-year heatwave intensity, compared to nearly 10 million/year under baseline climate conditions (1981-2010). At 2°C, this further grows to 172 million/year. With unmitigated climate change (3°C in 2100), the number of people annually exposed to this intensity of heat climbs to nearly 300 million per year, meaning that more than half of the European population could be exposed each year to a present 50-year heatwave.

Assuming present vulnerability and no additional adaptation, annual fatalities from extreme heat in 2100 could rise from 2,750 deaths now to 30,000 at 1.5°C global warming, 52,000 at 2°C and 96,000 at 3°C. The rise in human exposure to and fatalities from extreme heat is most pronounced in southern European countries and the highest number of fatalities will occur in France, Italy and Spain.

Milder winters will reduce exposure to extreme cold by 50% at 1.5°C global warming, 60% at 2.0°C and more than 80% at 3°C (Figure 2). The number of reported fatalities in recent years is already much smaller than those from heatwaves (100 fatalities/year over the period 1980-2016). This will further drop as a result of global warming.

base	1.5˚C	2.0˚C	3.0˚C
People annually exposed to a 50-year cold wave (million)			
9.6	5.1	2.8	1.2
Annual fatalities from cold waves			
79	34	20	9

Figure 2. Human exposure to and fatalities from cold waves in the EU and UK for different warming levels in 2100.

Total effect of climate change on temperature-related premature mortality

Global warming will result in a strong net increase in exposure to and fatalities from temperature extremes. However, this only captures part of the effects of climate change on temperature-related premature deaths. The mortality burden attributable to non-extreme below-optimum ambient temperature will likely decrease with global warming, while fatalities linked to non-extreme above-optimum temperatures will increase. Currently, with most of the temperature-related mortality burden attributable to non-extreme below-optimum temperatures (cold), it is unclear what the net effects of climate change will be on total premature temperature-related human mortality.

Socioeconomic drivers of future human risks of heat and cold extremes

Population ageing in Europe, which emerges as a major demographic trend for the coming decades, could further increase the effect on human beings of temperature extremes. Further, increasing urbanisation could amplify the urban heat island effect, which causes urban and metropolitan areas to be significantly warmer than their surrounding rural areas. The combined effects of heatwaves and air pollution might further exacerbate human stress in densely populated areas.

Adaptation to temperature extremes

Even with stringent mitigation action and limiting global warming to 1.5 or 2°C, the rise in people exposed to extreme heat could be manifold. Hence, societies will need to increase their resilience to cope with more frequent and intense heatwaves. There exist a wide range of adaptation measures, including improved design and insulation of houses, schools and hospitals, education and awareness raising of potential risk factors and recommended responses, and early warning systems. It is also important to consider other impacts of extreme temperature on ambient quality, such as ozone pollution under heatwaves, in order to identify the most appropriate response. In the medium- to long term (5 to 15 years and over 15 years respectively)[1], sound urban planning should aim to minimise the urban heat island effect. This can be achieved, for example, by increasing tree and vegetative cover, installing green or reflecting roofs, or using cool pavements (either reflective or permeable). There is a substantial lack of observations and quantitative information on the effectiveness of these measures, yet several of them can provide important co-benefits, such as reduced energy-demand of thermo-efficient buildings, or water retention and mental health benefits of green spaces.

Approach

The PESETA IV task on human impacts of heat and cold extremes provides a quantitative assessment of human exposure to and mortality from these extremes in Europe. The methodology integrates empirical data on human losses from disasters, past climate information, EUROSTAT demographic data and high resolution climate and socio-economic projections. As is common to all PESETA IV impact categories, the analysis first evaluates heat and cold wave mortality in a comparative static socio-economic setting, therefore only considering the influence of the climate change signal. This is done by comparing human impacts on present population under baseline climate (1981-2010) and climate at 1.5, 2 and 3°C global warming above preindustrial levels. In addition, we also provide a dynamic socio-economic assessment considering the 2015 Ageing Report projections of population, and look at how heat and cold extremes at the different warming levels would impact EU population projected for 2050 and 2100. As a 3°C warming scenario is unrealistic by mid-century, only the Paris targets are considered in 2050. Our impact estimates do not consider adaptation (i.e. assumption of unchanged mortality rates as derived from recent disaster loss records).

[1] As defined by CoMO (2016). Mayors Adapt - Reporting Guidelines. Brussels: Covenant of Mayors Office.

1 Introduction

Extreme temperature events can result in disastrous consequences, including lives lost and severe health issues (Arbuthnot et al., 2016). Notable recent examples in Europe are the 2003 and 2010 mega-heatwaves that likely broke the 500-year-long seasonal temperature records over approximately 50% of Europe (Barriopedro et al., 2011). Also this summer, at the end of June and in July 2019, two record-breaking heatwaves took place in Western Europe. The spatial extent of broken historical records during these events includes most of France, the Benelux, Switzerland, Western Germany, Eastern U.K. and Northern Italy. In Belgium and the Netherlands, recorded temperatures exceeded 40°C for the first time[2].

In Europe, heatwaves are one of the most lethal weather-related hazards. According to Munich Re's NatCatSERVICE[3] disaster database, more than 2000 heat-related fatalities per year were reported in the EU and UK during the period 1980-2017. Climate change effects on health has recently become a key priority for national, European and global institutions. For the World Health Organization climate change is now among the four top priorities.

Global warming and the intensification of climate change, with more frequent and intense extreme events, will have a direct impact on European population. Many studies investigated future projections of extreme temperatures and heatwaves at both global and continental scale (e.g. Meehl and Tebaldi 2004, Russo et al., 2014, Russo et al., 2015, Lehner et al., 2018, Dosio 2017). Fewer studies evaluated the mortality due to heat in view of climate change (e.g., Mora et al., 2017, Gasparrini et al., 2017; Forzieri et al., 2017). To date, projections of extreme heatwaves and their impacts for mitigation (1.5 °C, 2 °C) and higher (3 °C) warming levels are not available. For more obvious reasons, the evolution of cold waves in view of climate change are less well studied.

A better understanding of the expected changes in temperature extremes can inform policy makers to develop strategies for managing the risk associated with such events. The scale and nature of the health impacts observed depends on the timing, intensity and duration of the extreme temperature event, the level of acclimatisation and adaptation of the local population, infrastructure and institutions available to help the society in coping with the prevailing climate. As such, the health effects of temperature extremes and the determinants of exposure and vulnerability are context specific.

We assess the number of people exposed to extreme temperatures and the number of fatalities from these extremes. Human impacts of climate change go much beyond mortality from heat and cold waves assessed in this study. This includes, for example, infectious disease threats, increased likelihood of vector- and water-borne diseases and food-borne infections, issues with food and nutrition security and agriculture, warming effects on environmental toxicology, air pollution, forced migration and conflict, and mental health effects. We further note that heat and cold extremes only capture part of temperature-related mortality, and not the total mortality burden attributable to non-optimum ambient temperature. Studies based on temperature–mortality associations across the whole temperature range suggest that most of the temperature-related mortality burden is attributable to cold. Further, the effect of temperature extremes is substantially less than that attributable to milder but non-optimum weather (Gasparrini et al., 2015).

[2] https://www.worldweatherattribution.org/wp-content/uploads/July2019heatwave.pdf
[3] https://natcatservice.munichre.com/

2 Methodology

This report presents the likely evolution of heat and cold waves and their risks for the population of Europe in view of global warming. As an indicator of heat and cold waves we used the Heat-Wave Magnitude Index daily (HWMId) and the Cold-Wave Magnitude Index daily (CWMId) (Russo et al., 2015). The percentile based indicators take into account the length and intensity of events, as both aspects are relevant for human impacts. They have been for calculated from an ensemble of high-resolution regional climate projections for RCP4.5 and RCP8.5, for which the daily temperature projections were bias-corrected.

Vulnerability here is defined as the human mortality rate, which is the number of fatalities from temperature extremes as a share of the population exposed to them. We assessed vulnerability to extreme heat and cold on the basis of impact records collected from disaster databases during the period 1980-2016. Information for each disaster entry include: hazard type, country, year, total number of deaths. A summary of the reported events is provided in Table A3. From the reported fatalities we computed the annual average number of deaths for each country for both heat and cold extremes.

The heat and cold wave risk assessment is based on the combination of the hazard, exposure and vulnerability. For the baseline (1981-2010) and 30-year time windows around global warming levels (GWLs) of 1.5, 2 and 3°C above preindustrial temperature, we combine the fraction of territory expected to annually experience harmful intensities of heat or cold waves (see section 1.1.4 of this Annex) with the exposure population layer (see section 1.2 of this Annex) and the mortality rates calculated from the reported fatalities (section 1.3) and exposed people for the baseline.

As is common to all PESETA IV impact analyses, we first evaluated heat and cold impacts of global warming on present population. This allows us to understand what would be the human impacts if climate conditions under different levels of warming would be imposed on today's society, without any assumptions on socio-economic developments over long time spans. In addition, we also assess the impacts at different warming levels on population in 2050 and 2100 for the EU Reference socio-economic scenario (2015 Ageing Report projections[4]). These analyses allow disentangling the effects of climate and demographic changes. The human vulnerability derived from recent extreme temperature events are assumed constant in the analysis, hence the results presented do not include any acclimatization to changing climate by people or additional adaptation measures. Our hazard analysis includes all EU member states plus a number of neighbouring countries (UK, Iceland, Norway, and Switzerland and Balkan countries). Human impacts are presented for EU countries and the UK. More details on the methodology can be found in Annex 1.

[4] 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.

3 Results

In the first part of the results section, we present the projected changes in extreme heat and cold waves to portray heat/cold hazard at high spatial resolution under the different warming levels. In the second part, we present results of the impact analysis, which was derived from the high resolution hazard and exposure information and then aggregated to national scale.

3.1 Heat and cold wave hazard

Figure 3 shows for the different global warming levels the frequency (in years) of a heatwave that in baseline (1981-2010) climate occurs once every 20 years. For example, a value of 4 in these maps indicates that a heatwave that now happens once every 20 years will happen every 4 years when that global warming level is reached, or 5 times more frequent. The results show that heatwaves will progressively and significantly increase in frequency all over Europe with global warming. Even when limiting global warming to 1.5°C, the frequency of extreme heatwaves would increase three-fold nearly everywhere in Europe. A more pronounced intensification in heatwaves is observed in southern Europe, where a current 20-year heatwave event could occur almost every year under high levels of warming (3°C). Under 2°C and 3°C warming, most of the EU territory will face severe heatwaves at least once every three to five years. This implies that Europe will experience an enhanced probability for heatwaves comparable to or greater in magnitude, extent and duration than the devastating extreme heatwaves in 2003 and 2010 (Russo et al., 2015).

On the other side, projections for cold waves show an opposite trend, with current cold extremes tending to gradually disappear in Europe with global warming. Moderate cold waves (2-year return period) will be observed only every 20 years in many areas in Scandinavia, Iceland, UK and in in some areas in Portugal, Spain and Italy under 3°C of warming (Figure 3).

Robustness of change was used as a measure of uncertainty associated with the projections. According to that, high model agreement is defined when at least 2/3 of models agree in the sign of change. The projected changes in hazard intensity and frequency present a high model agreement in the increase (decrease) of heat (cold) waves for all warming levels throughout Europe.

3.2 Human impacts of heat and cold waves

Human heat- and cold-wave vulnerability describes the relationship between the exposure of humans to a heat or cold wave and the corresponding impacts. Both high and low temperatures, indoors and outdoors, pose substantial risks to human health, including increases in mortality, morbidity and health service use. Table 1 summarizes the most common direct consequences of heat and cold waves to human health. Particularly, heatwaves cause specific heat-related illnesses such as heat cramps, heat rash, heat oedema, heat syncope (dizziness and fainting due to dehydration), and heat exhaustion which can lead to potentially fatal heatstroke.

Moreover, health impacts may be direct, caused by the direct effect of the hazard or indirect, caused by the consequences of the hazard such as changes in behaviour or impact on services. Direct health impacts occur when a stable body temperature cannot be maintained (e.g. when temperatures are too extreme), when clothing or shelter is not suitable or when physiological responses are impaired.

Indirect impacts, occur when related services are affected. For instance, the impact on health services may be mediated through increasing demand for care, direct and indirect impacts on staff, which affect their ability to work, or ambulance response times. Temperatures extremes may have impacts on wider infrastructure that is essential for health, such as power, water and transport.

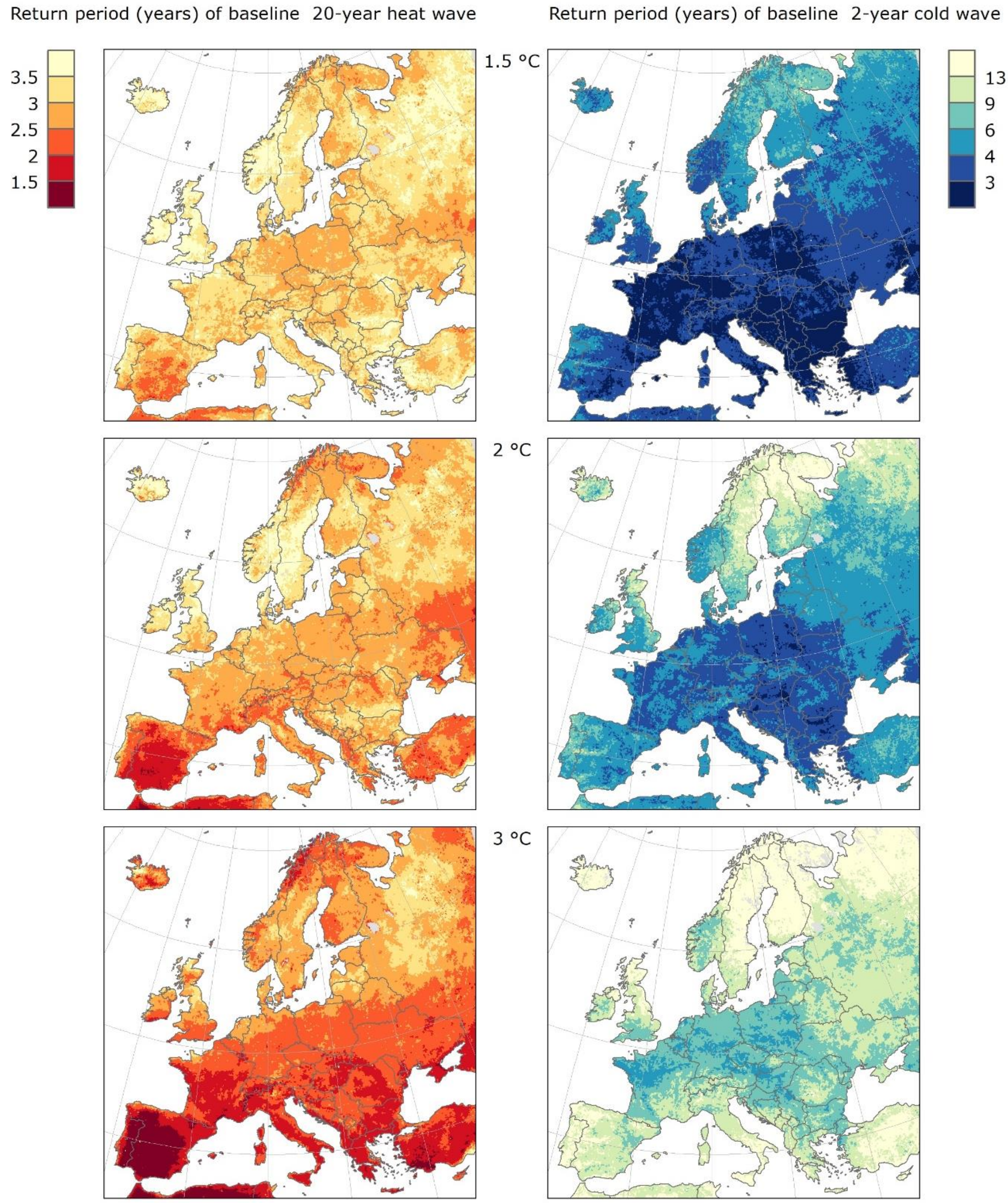

Figure 3. Return period (in years) of baseline 20-year heatwave and a 2-year cold wave for 1.5°C, 2°C and 3°C global warming.

Table 1. Direct consequences of Heat- and Cold-waves to human health and corresponding human susceptibility. Adapted from Forizeri et al. (2017).

	Heatwaves	Cold waves
Direct consequences for human health	Heatstroke, cardiovascular, cerebrovascular and respiratory diseases, premature mortality	Arterial thrombosis, cardiovascular, cerebrovascular, circulatory and respiratory disease, influenza epidemics, premature mortality
Human susceptibility	Older people due to impaired temperature regulation, children and people in stressful occupations, with pre-existing illness or socially isolated	Older people due to impaired temperature regulation and socially isolated people

3.3 Reported human impacts of extreme heat and cold

In this report, we analysed heat and cold wave disaster records collected over 1981-2016 in the Munich Re's NatCatSERVICE disaster and EM-DAT databases. The information recorded is the number of fatalities, with an indication of the timing and region (or country) where the event happened.

Figure A1 shows the evolution in time of the number of reported events and fatalities for heat and cold extremes in Europe between 1981 and 2016. Table A3 presents the total number of reported events and fatalities over the reference period for each European country, for heat and cold waves respectively. These data show that: i) the two risks are widespread in Europe; ii) heatwaves have been reported mainly in south European countries and can have catastrophic impacts on population through heatstroke, cardiovascular, cerebrovascular and respiratory diseases, and eventually premature mortality; iii) cold waves have been reported mainly in Central and North European countries, with cardiovascular stress and increased respiratory infections. The number of reported fatalities is much higher for heatwaves compared to cold waves. It should also be noted that the effect on people of days of extreme temperature is substantially less than that attributable to milder but non-optimum weather, with most of the temperature-related mortality burden attributable to below-optimum (i.e. cold) temperatures (Gasparrini et al., 2015).

The total number of reported events in time shows an increasing trend in the analysed period for both heat and cold waves. The total reported fatalities caused by heatwave over the period 1981-2016 sum up to 84,071 (3,980 for cold wave) or an average of 2,272 per year (108 per year for cold wave). Although reported fatalities induced by heatwave show an increasing trend in time, this is strongly influenced by the catastrophic event that occurred in 2003. On the other side, no statistically significant trend is are observed for cold wave human impacts.

3.4 Projections of human impacts of extreme heat and cold

In the EU and UK, 9.6 million people are at present expected to be exposed each year to a 50-year or more extreme heatwave event, which represents extreme heat conditions such as those experienced in the summer of 2003. With a probability to occur once every 50 years in present climate, by definition this implies that under present climate conditions 1/50 of the population is expected to be annually exposed to such event. Assuming static population, the number of people that is expected to be exposed per year to such intensity of extreme heat progressively grows with global warming, to 107 million at 1.5°C, 176 million at 2.0°C, and 307 million at 3.0°C. Hence, more than half of the European population could be exposed to extreme heat if no mitigation measures are taken, compared with 5% of the population for baseline climate (1981-2010) (Table 2).

In case of no additional adaptation, the strong increase in exposure with global warming would result in a rapid rise in the death toll from extreme heat in Europe. During the reference period, around 2,752 Europeans lose their lives each year because of extreme hot temperatures. Note that this number is an estimate based on reported fatalities in disaster loss databases over the period 1980-2016, and true figures are likely much higher. As depicted in *Table A8* most of these fatalities were registered in Southern Europe (1,433) and Central Europe South (746). According to our developed statistical approach, if no adaptation measures are implemented, this number rises to 30,000 deaths at 1.5°C (about a ten-time increase), around 52,000 at 2°C and approximately 95,000 at 3°C (more than a 30-fold increase).

Heatwaves, human exposure and projected fatalities will rise strongly everywhere in Europe. Yet, there is a latitudinal gradient of increasing impacts towards southern Europe (Figure 4). Southern European countries like Cyprus, Greece, Malta and Spain could see a 40-fold increase in mortality from heatwaves if no stringent mitigation actions are taken (Table A10) and no adaptation measures are implemented.

Population dynamics projected by the EU Reference scenario have a minor effect on the overall increase in risk related to extreme temperatures in Europe (Table 2). When demographic changes are taken into account, the number of people exposed to and fatalities from heat extremes is slightly higher in 2050 and drops again by 2100, as a result of the projected decline in population towards the end of the century (Table A2). Other non-climatic factors that will affect exposure to and human impacts from extreme heat and cold are the increase in vulnerable people (ageing population) and city dwellers, as well as land use and urban planning.

Table 2. Summary for EU and UK of projected changes in exposure and fatalities related to heat and cold extremes.

EU+UK		heat exposure	heat fatalities	cold exposure	cold fatalities
Present population	**base**	9,620,776	2,752	9,620,776	77
	1.5°C	107,821,398	30,194	5,112,878	43
	2.0°C	176,270,043	52,182	2,826,614	25
	3.0°C	307,144,027	95,337	1,226,096	11
Population 2050	**1.5°C**	112,455,255	30,650	5,338,071	41
	2.0°C	183,068,319	52,666	2,924,151	24
Population 2100	**1.5°C**	103,363,515	28,810	4,964,788	33
	2.0°C	167,987,746	49,375	2,688,268	19
	3.0°C	288,578,248	89,644	1,189,432	8

Table 3. Summary of relative changes in exposure and fatalities related to heat and cold extremes.

EU+UK		heat exposure	heat fatalities	cold exposure	cold fatalities
Present population	**base**	100%	100%	100%	100%
	1.5°C	1121%	1097%	53%	55%
	2.0°C	1832%	1896%	29%	33%
	3.0°C	3193%	3464%	13%	14%
Population 2050	**1.5°C**	1169%	1114%	55%	53%
	2.0°C	1903%	1914%	30%	31%
Population 2100	**1.5°C**	1074%	1047%	52%	43%
	2.0°C	1746%	1794%	28%	25%
	3.0°C	3000%	3257%	12%	11%

Older people are particularly vulnerable to extreme heat and suffer increased fatalities from cardiac and respiratory disease during heatwaves. The EU Reference Scenario projects that in EU and UK the share of people older than 65 years will increase from 19% now to 30% by the end of this century (Table A2), with the highest shares in some southern European countries such as Portugal, Greece and Italy. This will likely increase the mortality rates from heat extremes in European populations.

Dense urban areas are often significantly warmer than the surrounding countryside, especially at night. The air temperature in dense cities can be 5 to 10°C warmer compared to the neighbouring rural areas. This is known as the urban heat island effect, and it is mainly related to the size of the urban centre, but also with other urban characteristics like the dominant type of building design or the total share of green areas. Europe is already characterised by a high level of urbanisation, with approximately 73% of its inhabitants living in urban areas. According to the EU Reference scenario, by 2050 and extra 27 million Europeans will live in urban areas. This will probably amplify extreme heat-induced effects through the urban heat island effect.

Greening of cities can reduce the urban heat island effect. Some EU funded projects like the URBAN Greenup project, LifeMedGreenRoof and the Quick Urban Forestation[5] explored and implemented nature-based approaches to minimise urban heating. Nature-based solutions are practices oriented to tackle socio-economic challenges by taking advantage of the power of nature. Within this context, targets include reducing the energy requirements of buildings by installing green roofs on them and promoting reforestation in the European cities. Strategically located shading trees directly reduce building temperatures by reducing the amount of solar energy that reaches a building’s surface, and vegetation cools the air through evapotranspiration. Furthermore, more vegetation means less pavement and more soil, and the increased water absorption of soil allows more evaporation to take place, thus cooling the surrounding air.

[5] http://www.buildup.eu/en/news/overview-alleviating-urban-heat-island-context-climate-change-0

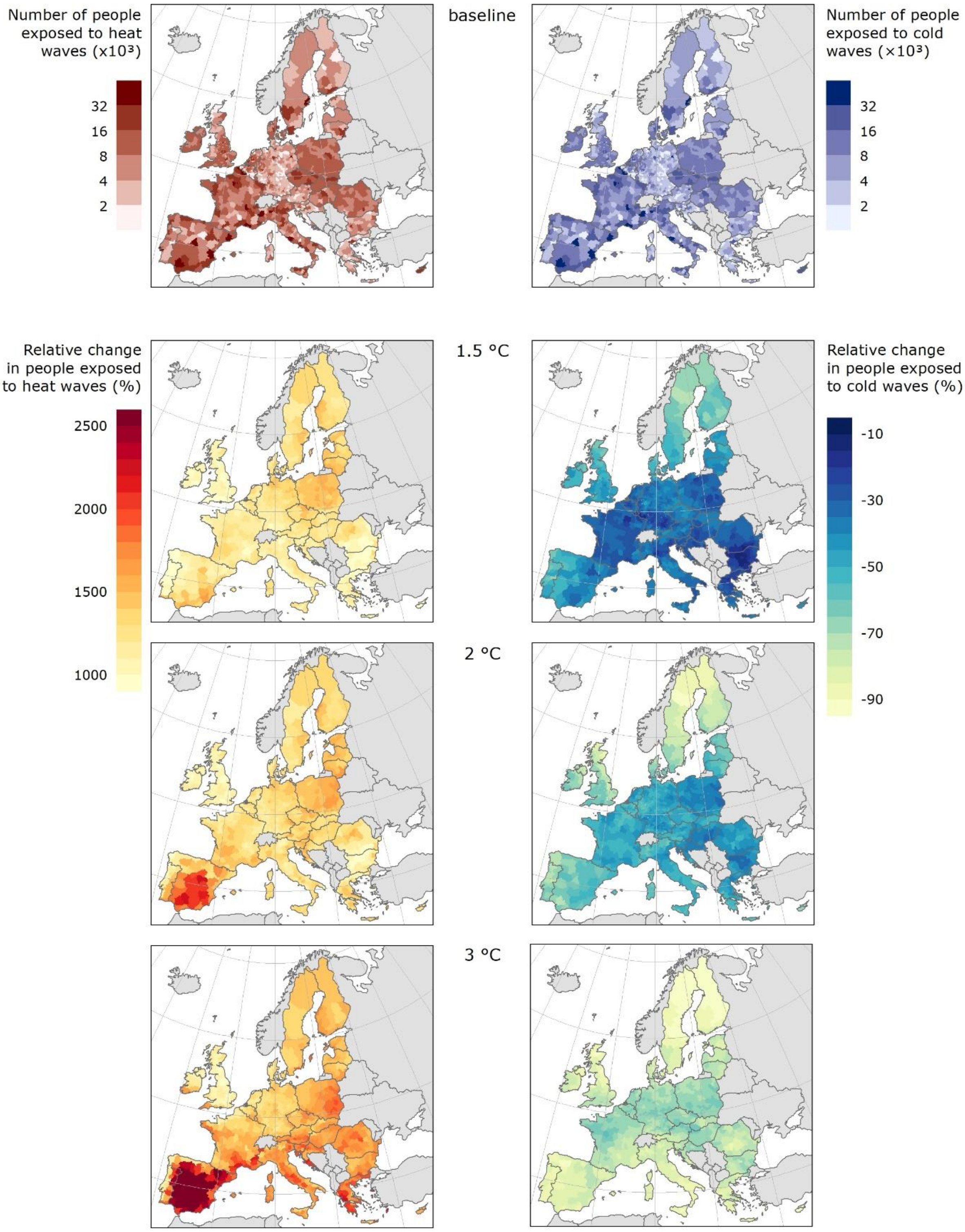

Figure 4. Number of people annually exposed to a present 50-year heatwave and cold wave (top row) and projected changes in human exposure to these events for 1.5°C, 2.0°C, and 3.0°C levels of global warming.

An opposite trend is projected for the people exposed to and fatalities from extreme cold events. The population annually exposed to extreme cold (50-year event) is projected to decrease from around 10 million in the baseline to 5 million at 1.5°C, 2.8 million at 2.0°C and 1.2 million at 3°C (Table 2). These strong decreases are widespread over all European countries with relative changes in a high warming scenario of -90% and more

(Table 3). The strongest absolute reductions in exposure to cold extremes are projected for southern and northern European countries (Figure 4), in the following order: Malta (-97%), Croatia (-96%), Finland (-94%), Portugal (-93%) and Sweden (-93%).

Similarly, the number of deaths related to extreme cold events in Europe is projected to significantly reduce (Table 2). For the baseline period, less than 100 fatalities were reported each year due to disasters related to extreme cold temperatures. Note that this is only a small fraction of the total number of people that indirectly die from milder below-optimum temperatures. Central European countries (e.g. Poland, Romania, and Hungary) reported the highest number of fatalities during the baseline period (Table A3). Global warming results in a prominent continent-wide decrease of mortality from extreme cold events, dropping to 43 annual deaths at 1.5°C, 25 at 2°C and around 11 fatalities/year at 3°C. Similar as for heatwaves could the increase in the number of people older than 65 years old result in slightly higher mortality from extreme cold than these estimates, as they are more vulnerable to cold extremes.

4 Conclusions

Results from this work show a strong and persistent increase in heatwaves and a reduction in extreme cold spells all over Europe. With unmitigated climate change, a current 50-year heatwave may occur almost every year in southern Europe, whereas in other regions of Europe such events may happen every 3 to 5 years. Cold waves on the other hand tend to disappear in Europe under high levels of warning (3°C).

In the absence of additional adaptation actions, this could result in a rapid rise in the death toll due to heat-related disasters in Europe, which is somewhat more pronounced in southern European countries. Extreme cold induced fatalities, which are much smaller in absolute terms than those from extreme heat, will strongly decrease in all regions of Europe and also somewhat more in southern Europe. The net balance is a strong increase of fatalities from heat and cold extremes with global warming. These estimates do not account for the strong increase projected in the number of people older than 65 years, which could further lead to higher mortality from heat and cold. Continued urbanisation in Europe could also increase the urban heat island effect and a higher number of people exposed to extreme heat conditions. As we noted earlier, the death toll from temperature extremes only represents a fraction of the total mortality burden from non-optimum ambient temperatures. Apart from the effects of temperature extremes as reported in this study, global warming will likely decrease the number of deaths from non-extreme below-optimum temperatures and increase mortality from non-extreme above-optimum temperatures. With most of the temperature-related mortality burden attributable to non-extreme below-optimum temperatures (cold), it is unclear what the net effects of climate change will be on premature temperature-related human mortality.

Our projections show that climate mitigation can considerably reduce the number of people exposed to and killed by extreme heat. Limiting warming to 1.5°C could reduce the number of heat fatalities by 200,000 per year compared to unmitigated climate (3°C of global warming). Yet, even when this stringent mitigation target is reached, the number of fatalities from extreme heat could still be ten-fold the number of deaths reported today. Hence, societies will need to adapt to be able to cope with the strong rise in heatwaves. With nearly three quarters of the European population living in an urban environment and the fact that temperatures can be more than 5 degrees higher in cities compared to the surrounding rural areas, it will be crucial to reshape our cities to minimize the urban heat island effect. Local scale studies have shown that greening of cities can be an effective way to achieve this. Greener cities also provide many other co-benefits, such as improving air quality, capturing emissions, saving of energy to heat and cool buildings, and being beneficial for the mental health of city dwellers.

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Annexes

Annex 1. Methodology

A1.1 Heat and cold wave hazard modelling

A1.1.1 Climate projections

Projections of extreme heat and cold hazard with 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. The daily temperature data simulated by the climate models were bias-corrected prior to calculating the extreme temperature indicators. 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 A1). 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 A1. Regional climate models (RCM) used in the heat and cold 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

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.

A1.1.2 Heat-Wave Magnitude Index daily (HWMId)

The HWMId as well as the CWMId are indicators designed to take into account both the length and intensity of the heat (cold) waves. In addition, their value is weighted with respect to the climatological maximum temperature interquartile range. In particular the value of HWMId it is proportional to the heat wave length, but it also depends, crucially, on the temperature anomaly with respect the climatological 25th percentile.

The HWMId is a numerical indicator that takes both the duration and the intensity of the heat wave into account. Basically, the magnitude index sums excess temperatures beyond a certain normalized threshold and merges durations and temperature anomalies of intense heat wave events into a single indicator, according to the methodology described in Russo et al. (2015).

The HWMId is an improved indicator based on the previously defined Heat Wave Magnitude Index (HWMI) depicted in Russo et al. (2014). The main limitation of the previous version of the indicator was the underestimation of extreme events due to problems in estimating the magnitude associated to events of very high temperature, particularly frequent in a changing climate. The HWMId overcome its limitations, and despite its novelty, it was applied in several studies related to climate change and operational forecasting (Zampieri et al., 2015; Forzieri et al., 2016; Russo et al., 2016; Lavaysse et al. 2018; Ceccherini et al., 2017; Dosio 2017, Russo et al. 2017).

The HWMId is defined as the maximum magnitude of heat waves in a year. Specifically, a heat wave is defined as a period ≥ 3 consecutive days with maximum temperature above a daily threshold calculated for a 30-year-long reference period. At least 30-year time series of daily vales are needed to obtain a robust estimation of the indicator. The threshold is defined as the 90th percentile of daily maxima temperature, centred on a 31-day window. Hence, for a given day d, the threshold is the 90th percentile of the set of data Ad defined by

$$A_d = \bigcup_{y=k}^{n} \bigcup_{i=d-15}^{i=d+15} T_{y,i}$$

Where *U* denotes the union of sets and T_y represents the daily T_{max} of the day *i* in year *y*. The interquartile range (*IQR*) defined as the difference between the 25th and 75th percentiles of the daily maximum temperatures is used as the heat wave magnitude unit (M_d), since it represents a non-parametric measure of the variability and defined as follows;

$$M_d(T_d) = \begin{cases} \dfrac{T_d - T_{30y25p}}{T_{30y75p} - T_{30y25p}} if T_d > T_{30y25p} \\ 0 if T_d \leq T_{30y25p} \end{cases}$$

with T_d being the daily T_{max} on day d of the heat wave, T_{30y25p} and T_{30y75p} represents the 25th and 75th percentile values respectively of the time series composed of 30 year annual values. For instance, if a day within a heat wave has a temperature value equal to the *IQR*, its corresponding magnitude value will be equal to 1. According to this definition, if the magnitude on the day d is 3, it means that the temperature anomaly on the day d is 3 times the *IQR*.

A1.1.3 Cold-Wave Magnitude Index daily (CWMId)

As defined for heat waves in the previous section, the occurrence and magnitude of cold waves are defined as three consecutive days with daily minimum temperature below the daily threshold defined as the 10th percentile of daily minima, centred on a 31-day window. In correspondence to the HWMId definition the Cold Wave Magnitude Index daily (CWMId) is defined as the minimum of the magnitude of all the cold waves in a year with negative values. The CWMId sums the negative magnitude of the consecutive days composing a cold wave. The retrieval of CWMId return levels follows the same approach as describe in the previous section for HWMId.

The daily temperatures required for the computation of the heat and cold waves were retrieved in each 11 km grid cell of the EURO-CORDEX domain from the set of eleven different GCM-RCM configurations under the RCP 4.5 and 8.5 emission scenarios (Table A1).

A1.1.4 Hazard occurrence probabilities

The hazard component (H) of the risk assessment is computed as the fraction of territory expected to annually experience harmful intensities of hot or cold waves. It was calculated by integrating the territory subject to hazard events (expressed by a discrete function f) over the probability of occurrence distribution of the hazard. The probabilities were retrieved through extreme value analysis of the annual maxima or minima depending on the occurrence of heat or cold extremes, respectively. For the future time windows, changes in the high-end tail of the frequency distribution (events with hazard intensity that now happen once every 50 years or less frequent) were translated into changes of the territory expected to be annually exposed to heat and cold extremes.

A1.2 Present and future exposure

We performed the heat and cold wave human impact assessment with static population conditions as well as with demographic projections in Europe. The static approach provides information on how climate and consequent heat and cold extremes 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 human exposure and fatalities of 1.5 and 2°C warming on 2050's society (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 society.

The demographic projections 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, market and demographic trends in the EU. High-resolution population projections based on the EU Reference Scenario were derived with the LUISA modelling platform (Jacobs-Crisioni et al., 2017). These maps capture the fine-scale processes of population dynamics (e.g., urban expansion, stagnation or de-growth, and concentration that represent key drivers of the future exposure of populations. We derive complementary information on the degree of urbanisation of municipalities and the share of older people (>65 years of age) for the present and future from the EU reference scenario. The information on exposure is summarized in (Table A2). As the Ageing report deals with projections only to the year 2060, the projections have been extended to the year 2100. 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).

Table A2. Summary of baseline and future human exposure. Total population for the different time slices (expressed in millions), change in urban population and change in the share of older people for each region and total EU+UK.

	population			urban	urban	age		
Country	**population 2011 (in million)**	**population 2050 (in million)**	**population 2100 (in million)**	**share urban population in 2011**	**share urban population in 2050**	**% people > 65 years in 2011**	**% people > 65 years in 2050**	**% people > 65 years in 2100**
Northern Europe	27	29	24	66%	68%	18%	28%	30%
UK and Ireland	68	82	91	60%	65%	15%	25%	27%
Central Europe N.	147	143	139	76%	83%	18%	27%	29%
Central Europe S.	117	125	100	63%	64%	18%	30%	30%
Southern Europe	141	141	139	71%	70%	19%	29%	31%
EU+UK	499	520	493	73%	75%	19%	29%	30%

A1.3 Vulnerability

We note that this study does not assess premature deaths across the whole temperature range. Rather, we focus on exposure to and excess fatalities from heat and cold extremes. Vulnerability (V) describes the relationship between the exposure to a temperature extreme and the human impact. It is quantified here as the ratio of the number of people killed by a heat or cold wave to the total population exposed to the hazard. The number of deaths have been obtained at country level from the Munich Re's NatCatSERVICE[6] and EM-DAT[7] disaster databases. Information for each disaster entry include: hazard type, country, year, total number of deaths. A summary of the reported events is provided in Table A3. Trends in these data have been evaluated for statistical significance using the Mann-Kendall test. The total number of reported events shows an increasing trend with p-value=0.02 and 0.03 for heat and cold waves, respectively. Reported fatalities from heat waves show an increasing trend with p-value=0.05, while changes in cold waves fatalities are not statistically significant (p-value=0.15). From the reported fatalities we computed the annual average number of deaths for each country for both heat and cold extremes.

While the two databases are among the most comprehensive sources of reported impacts of weather-related disasters, recorded casualties very likely deviate from the true numbers. This is evident for deaths due to heat waves in northern countries that have been documented in the media but are missing from the database. Possible biases imputable to incomplete data recording could partially explain relevant differences in reported fatalities between countries with similar climate background and adaptation capacity (e.g. no fatalities due to heat waves reported in Slovakia in 30 years, which is a spatially distributed hazard, versus 500 in Hungary and more than 400 in the Czechia). In order to solve the problem of data incompleteness we derived baseline deaths for each country with missing fatal disaster records as a function of the deaths documented in the corresponding macro-region and its population and GDP (more details can be found in Forzieri et al., 2017).

The vulnerability (V) component was quantified at country level and was considered to be static over time, thus assuming that no changes in human susceptibility factors occurred and no additional measures were taken to reduce the impact of disasters or enhance human acclimatization to future extreme climate conditions. While we recognize that this is likely unrealistic, implementing a static approach has the advantage that hypotheses on the future evolution of human vulnerability over the coming decades are not needed. This simplifies the interpretation of the results and minimizes the number of assumptions whose uncertainties could be large and are not quantifiable, especially with respect to the future evolution of adaptation capacity.

The estimates of baseline and future human fatalities from temperature extremes reported herein are fully conditional on the recorded impacts. Hence, any deviations of the reported deaths from the true impacts are inherently translated into our vulnerability estimates and thus into future human losses.

A1.4 Impact modelling

The heat and cold wave risk assessment is based on the combination of the hazard, exposure and vulnerability (IPCC, 2012). For the baseline (1981-2010) and 30-year time windows around the warming levels, we combine the fraction of territory expected to annually experience harmful intensities of heat or cold waves (see section 1.1.4 of this Annex) with the exposure population layer (see section 1.2 of this Annex) and the mortality rates calculated from the reported fatalities (section 1.3) and exposed people for the baseline. For the static analysis, population maps were kept constant, for the 2050 and 2100 impact analysis, projected population maps were used.

In our analysis we assume that human impacts are linked to events that happen every 50 years or less frequent in present climate. In reality, it is possible that, more frequent (i.e. less extreme) extreme temperature events induce human losses, or that impacts are avoided or minimized for more extreme events. For future time windows, we then translated changes in this high-end tail of the frequency distribution to project future impacts. Hence, we assume that the changes in the part of the frequency distribution that we consider to be linked with human impacts (current 50-year or more extreme events) are representative of the true changes in the frequency of temperature extremes.

Impact modelling outcomes were aggregated and presented for the following European macro regions:

- **Northern Europe:** Sweden, Finland, Estonia, Lithuania, Latvia and Denmark
- **UK and Ireland:** UK and Ireland
- **Central Europe North:** Belgium, Germany, Luxemburg, Netherlands, Poland
- **Central Europe South:** Austria, Czech Republic, France, Hungary, Slovakia, Romania
- **Southern Europe:** Bulgaria, Croatia, Cyprus, Greece, Italy, Malta, Portugal, Slovenia, Spain.

[6] http://www.munichre.com/natcatservice
[7] https://www.emdat.be

Annex 2. Extended results

A2.2 Description of impact estimates at country scale

The following section presents the detailed statistics on persons exposed and expected fatalities for the regions analysed.

Table A3. Summary of reported heat and cold wave impacts in Europe. Number of reported heat- and cold- wave events and related fatalities from MunichRe's NatCatSERVICE and EM-DAT over the period 1980-2017.

	heat		cold	
Region	**nr events**	**fatalities**	**nr events**	**fatalities**
Northern Europe	4	32	47	163
UK and Ireland	3	2,747	47	175
Central Europe N.	17	14,017	78	2,266
Central Europe S.	25	25,589	94	1,060
Southern Europe	33	41,686	99	315
EU+UK	82	84,071	365	3,980

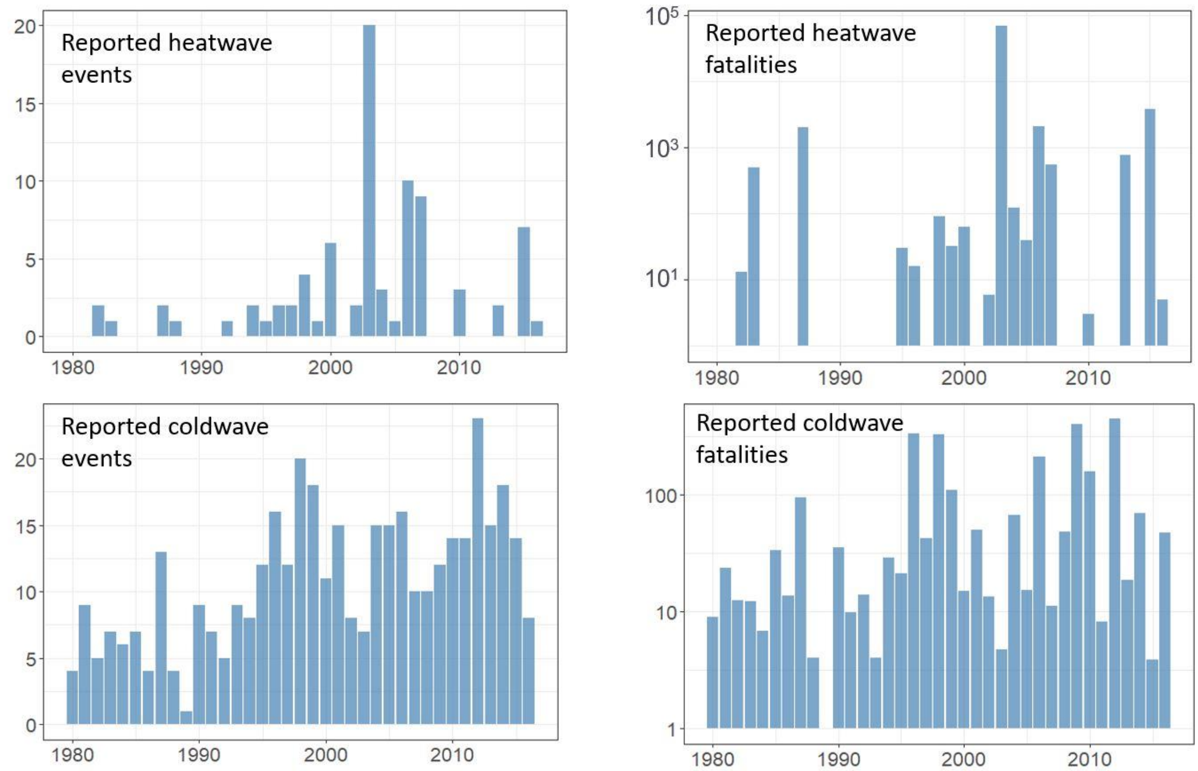

Figure A1. Evolution in time of the number of reported heat and cold-wave events and fatalities in Europe between 1980 and 2016. Please note that the vertical scale for reported fatalities for heatwaves and cold wave is different.

Table A4. Regional values of current and future number of people exposed to heat waves. Numbers are expressed as thousands of people.

	Base economy				Economy 2050		Economy 2100		
Region	**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**
Northern Europe	511	6,345	9,492	15,440	6,929	10,272	5,753	8,566	14,088
UK and Ireland	1,286	12,643	19,637	28,988	15,350	23,839	16,973	26,360	38,874
Central Europe N.	2,921	35,169	53,922	87,233	34,089	52,205	32,778	50,140	80,876
Central Europe S.	2,306	25,753	42,103	74,369	27,612	45,203	22,045	36,061	63,077
Southern Europe	2,595	27,911	51,117	101,113	27,866	50,775	27,708	51,165	101,503
EU+UK	9,618	107,821	176,270	307,144	111,847	182,294	105,257	172,293	298,417

Table A5. Reginal values of current and future number of people exposed to cold waves. Numbers are expressed as thousands of people.

	Base economy				Economy 2050		Economy 2100		
Region	**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**
Northern Europe	511	198	101	44	212	106	177	90	39
UK and Ireland	1,286	568	263	140	691	320	764	354	188
Central Europe N.	2,921	1,664	979	465	1,622	947	1,577	911	439
Central Europe S.	2,306	1,327	756	340	1,421	806	1,127	642	292
Southern Europe	2,595	1,355	727	237	1,361	729	1,328	708	230
EU+UK	9,618	5,113	2,827	1,226	5,306	2,909	4,973	2,705	1,189

Table A6. Regional values of expected annual people exposed per 1 million inhabitants to present 50-year heat wave for baseline climate (1981-2010) and different warming levels.

	Base economy			
Region	**base**	**1.5°C**	**2.0°C**	**3.0°C**
Northern Europe	20,000	253,202	389,650	597,376
UK and Ireland	20,000	199,688	312,866	495,879
Central Europe N.	20,000	235,637	359,803	600,308
Central Europe S.	20,000	229,056	370,746	652,673
Southern Europe	20,000	219,535	410,644	773,786
EU+UK	20,000	230,247	381,533	659,202

Table A7. Regional values of expected annual people exposed per 1 million inhabitants to present 50-year cold wave for baseline climate (1981-2010) and different warming levels.

	Base economy			
Region	**base**	**1.5°C**	**2.0°C**	**3.0°C**
Northern Europe	20,000	8,280	4,460	1,982
UK and Ireland	20,000	8,429	3,968	2,078
Central Europe N.	20,000	11,842	6,529	3,208
Central Europe S.	20,000	11,221	6,739	2,976
Southern Europe	20,000	10,733	5,962	1,840
EU+UK	20,000	10,345	5,766	2,375

Table A8. Regional values of current and future fatalities due to heat extremes.

	Base economy				Economy 2050		Economy 2100		
Region	**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**
Northern Europe	6	76	117	179	73	111	66	101	156
UK and Ireland	95	942	1,470	2,259	1,112	1,735	1,237	1,929	2,955
Central Europe N.	472	5,466	8,334	13,376	5,589	8,513	5,859	8,926	14,352
Central Europe S.	746	8,235	13,637	23,318	9,425	15,609	7,238	11,984	20,473
Southern Europe	1,433	15,527	28,675	56,382	15,795	28,961	15,886	29,479	58,263
EU+UK	2,752	30,247	52,233	95,514	31,994	54,928	30,285	52,419	96,199

Table A9. Regional values of current and future fatalities due to cold extremes.

	Base economy				Economy 2050		Economy 2100		
Region	**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**
Northern Europe	7	3	2	1	3	1	3	1	1
UK and Ireland	5	2	1	1	3	1	3	1	1
Central Europe N.	31	18	11	5	16	10	13	8	4
Central Europe S.	27	16	9	4	15	9	12	7	3
Southern Europe	9	5	3	1	5	3	4	2	1
EU+UK	79	44	26	11	41	24	34	20	9

Table A10. Ratio change with respect to baseline of fatalities from heat waves.

	Base economy				Economy 2050		Economy 2100		
Region	**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**
Northern Europe	1	13	19	30	12	18	11	17	26
UK and Ireland	1	10	16	25	12	18	13	20	32
Central Europe N.	1	12	18	30	14	22	13	21	35
Central Europe S.	1	11	19	33	12	19	10	16	28
Southern Europe	1	11	21	39	11	21	10	19	36
EU+UK	1	11	18	31	12	20	11	19	31

List of abbreviations and definitions

EAPE	Expected Annual People Exposed
GDP	Gross Domestic Product
GCM	Global Climate Model
HWMId	Heat Wave Magnitude Index daily
CWMId	Cold Wave Magnitude Index daily
RCP	Representative Concentration Pathway
RCM	Regional Climate Model

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