Title:

Will climate warming decrease winter mortality in Europe?

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Manuscript submitted to Nature Climate Change

Recent studies have vividly emphasized the lack of consensus on the contribution of climate warming to the recent and future evolution of winter mortality. Here we show the link between daily temperature and numbers of deaths to characterize the spatial picture of human vulnerability to winter conditions in nearly 200 European regions representing more than 400 million people. Analyses indicate that only the United Kingdom, the Netherlands and Belgium have successfully adapted to harsh winters, while the other countries still remain exposed to the year-to-year fluctuations in seasonal temperatures. Our theoretical approach is found to successfully reconcile the apparent contradictions between recent studies, showing that climate warming will contribute to the decline of winter mortality in most, albeit not all, the regions. The different sensitivity of European societies to cold temperatures highlights the kind of adaptation strategies that each country has already implemented and could potentially take in order to increase the overall life expectancy.

Many vulnerable aspects of natural systems and human populations (Patz et al. 2005, Costello et al. 2009, IPCC 2014) are under threat from the continuous rise in global temperatures induced by anthropogenic greenhouse gas emissions (IPCC 2013). Europe emerges as an especially responsive area to climate change, with more frequent, longer and harsher summer heat waves (Meehl and Tebaldi 2004; Ballester et al. 2009,2010a,2010b) and less frequent, shorter and milder winter cold spells (Ballester et al. 2009,2010b; deVries et al. 2012). The most direct way in which global warming is expected to affect public health in Europe relates to changes in mortality rates associated with the exposure to ambient temperatures (Ballester et al. 2011, Hajat et al. 2014).

The link between atmospheric temperature and human mortality has been extensively characterized in the literature (Kunst et al. 1993, The Eurowinter Group 1997, Kalkstein and Greene 1997, Keatinge et al. 2000, Healy 2003, Carson et al. 2006, Simonsen et al. 2007, Christidis et al. 2010, Ballester et al. 2011, Huang et al. 2012, Martin et al. 2012, Morabito et al. 2012, Robine et al. 2012, Li et al. 2013, Benmarhnia et al. 2014, Bennett et al. 2014, Hajat et al. 2014, Lowe et al. 2015). Once the capacity of the human body to mitigate the external sources of heat stress is exceeded, risk of homeostatic failure (Kettaneh et al. 2010), disease exacerbation and death rapidly start to increase (McMichael et al. 2012). The exposure to cold winter temperatures is instead associated with direct effects such as hypothermia, but especially with indirect pathologies such as cerebrovascular disorders, ischaemic heart disease or respiratory infections (The Eurowinter Group 1997, Simonsen et al. 2007).

The risk of death in a society is also influenced by a number of socioeconomic factors, such as the macroeconomic situation of the country, the level of income poverty and inequality, the amount of government expenditure on education and health or simply the kind of lifestyle and habits of human individuals (Healy 2003). On the contrary, the degree of exposure to environmental temperatures can be reduced through socioeconomic progress (Kunsk et al. 1990) and by means of physiological, behavioral and cultural adaptations of the society (McMichael et al. 2006), such as improvements in prevention, healthcare and early warning systems, the design of action plans for deprived people, a systematic vaccination against influenza (Simonsen et al. 2007), a change for healthier diets or a better acclimatization and insulation of buildings (Healy 2003, Christidis et al. 2010, Kettaneh et al. 2010).

The record-breaking summer 2003 heat wave, which has been described as an event sharing similar characteristics with future summers simulated by state-of-the-art climate models for the end of the 21st century (Schär et al. 2004), caused 70,000 excess deaths in western Europe (Robine et al. 2008). Mortality projections inferred from transient climate change simulations for the present century point to a steady decreasing (rising) trend in cold- (heat-) related mortality (Ballester et al. 2011). Nonetheless, the scientific community has long debated the net contribution of global warming to overall annual mortality, i.e. whether the increase in the summer counts of deaths will be totally (Keatinge et al. 2000, Christidis et al. 2010, Ballester et al. 2011, Martin et al. 2012) or only partially (Kalkstein and Greene 1997, Morabito et al. 2012, Huang et al. 2012, Li et al. 2013, Hajat et al. 2014) offset by the decline in winter mortality. These projections are still subject to huge uncertainties, such as in the methodology used to model the relationship between environmental variables and mortality (Benmarhnia et al. 2014), the set of assumptions made in order to estimate the future evolution of the sociodemographic profile (e.g. age pyramid or macroeconomic indicators) or the degree of adaptation of human societies to rising summer and winter temperatures (Ballester et al. 2011).

In a recent study, Staddon et al. (2014, hereafter SMD14) increased the complexity of this challenging puzzle by showing that the year-to-year association between excess winter deaths and winter temperatures has progressively disappeared in England and Wales during the second half of the twentieth century. They extrapolated this result to conclude that climate warming will not decrease winter mortality in economically developed societies such as Europe, Canada and the United States. Here we test this hypothesis by evaluating the relationship between winter temperatures and numbers of deaths in 187 NUTS2 regions (i.e. second level of the Nomenclature of Territorial Units for Statistics; Robine et al. 2008, Ballester et al. 2011) representing more than 400 million people in western Europe. For the first time, our study comprehensively characterizes the spatial picture of human vulnerability to winter conditions at the continental level, showing that the vast majority (81%) of the European population still remains exposed to climate variability, concluding that global warming will contribute to the overall decrease in winter mortality.

In the search of the spatial picture of current human vulnerability to winter conditions, Figure 1a shows the correlation map between the annual time series of winter mean temperature and mortality for each of the European regions. This figure confirms the lack of a strong year-to-year relationship in England and Wales for the present period (-0.12, Table 1a), which is coherent with the small correlation between excess winter deaths and winter day frequency found in SMD14 for the same period. The absence of a year-to-year dependency is found in very few other regions: the Netherlands, Belgium and two northern regions in France (Nord-Pas-de-Calais and Picardie). Large year-to-year correlations are instead found in all the other countries included in the domain of study, ranging from -0.97 in Portugal to -0.60 in Denmark (Table 1a). The sharp contrast between correlation values in neighboring regions of the Netherlands, Belgium and Germany suggests that the spatial distribution of the year-to-year relationship is not primarily linked to differences in climatological winter conditions, which are predominantly characterized by large-scale synoptic atmospheric patterns across political borders. Thus, correlations in the Netherlands and Belgium are close to zero, while values in the neighboring German regions of Rhineland-Palatinate, Lower Saxony and Rhine-Westphalia are -0.79, -0.74 and -0.71, respectively. Indeed, the ensemble of correlations of the 16 regions in Germany are significantly different from the values in the Netherlands and Belgium ($p < 0.001$), ranging from -0.92 to -0.65 except in the particular case of the small city-state of Bremen (-0.44).

Nonetheless, the spatial picture of human vulnerability to cold conditions is not only determined by the year-to-year association between seasonal mean temperature and mortality shown in Figure 1a, but also at the intraseasonal timescale. It is well know that the relationship between daily temperatures and counts of deaths displays an asymmetric U-, V- or J-shape with monotonically increasing incidence rates for temperatures warmer or colder than the temperature interval of minimum mortality (Supplementary Figure 1; Huynen et al. 2001, McMichael et al. 2006, Christidis et al. 2010). This so-called comfort temperature is found to be between 4°C and 9°C warmer than the annual mean temperature (Figure 2; see also Ballester et al. 2011), and therefore the cold part of the daily temperature/mortality relationship covers a larger range of temperatures and calendar days. At the same time, however, the increase in mortality per unit of temperature is generally steeper in the warm part of the relationship (Supplementary Figure 1). The combination of these two opposing factors explains the nonmonotonic long-term projection of future annual mean mortality inferred by Ballester et al. (2011), with an increase of heat-related mortality that will be totally (only partially) offset until (after) 2040 by the decline in the counts of deaths due to cold temperatures.

The European map of human sensitivity to cold days and extremes is depicted in Figure 1b as the regression coefficient between daily temperature and mortality data during the winter season. This dependency is shown to be approximately linear in all the countries (Supplementary Figure 1), and therefore the regression coefficient describes the sensitivity to cold temperatures for all kind (i.e. mild, moderate and extreme) of winter days. The map illustrates the paradox of winter mortality, in which the highest vulnerability to cold days is found in the temperate regions of southern Europe: -1.13, -0.67 and -0.52 daily cases/million/°C in Portugal, Spain and Italy, respectively (Table 1b). This apparent paradox is explained by multiple factors (Healy 2003), such as the better housing insulation in the areas with severe climatological winter conditions in central and eastern Europe. Thus, the lowest regression coefficients of daily data are found in the Netherlands, Switzerland and Germany (-0.14, -0.15 and -0.16 daily cases/million/°C, respectively; Table 1b). The contrast between the larger vulnerability in the southern regions and the higher degree of acclimatization in the northeastern countries is better expressed through the largely negative correlation between climatological winter mean temperatures and the regression coefficients of daily data at the regional level (-0.74, Supplementary Figure 2).

It is important to note that the United Kingdom is the fourth country with higher day-to-day regression coefficient (-0.38 daily cases/million/°C), but in contrast it is the third country the least exposed to harsh winters (year-to-year correlation of -0.12, Table 1a,b). The opposite situation is found in many countries in central Europe (e.g. Switzerland, with a year-to-year correlation of -0.88 and a day-to-day regression of -0.15 daily cases/million/°C, Table 1a,b). The different degree of adaptation to seasonal mean temperatures and cold winter days highlights the different spatial distribution of the vulnerability to year-to-year and day-to-day winter temperature anomalies (cf. Figures 1a,b).

These spatial differences are currently generating a vivid scientific debate. In the particular case of the United Kingdom, SMD14 compared socio-demographic data between 1951-1976 and 1976-2011 and pointed to increased help for vulnerable sections of the population and improvements in housing, standards of living and healthcare systems as primary factors explaining the progressively declining year-to-year association between excess winter deaths and winter mean temperatures. This result, which is coherent with the year-to-year correlation map depicted in Figure 1a, was seen to be largely explained by the decreasing influence of housing quality and cold temperatures and the growing impact of flu activity (SMD14). Similarly, Carson et al. (2006) showed the declining year-to-year variability and trend in (all cause, cardiovascular, respiratory and non-cardiorespiratory) winter mortality in the city of London during the last century.

On the contrary, other authors have studied the spatial covariance between several socio-demographic factors and the vulnerability to cold temperatures during the last quarter of the twentieth century, and they found a spatial distribution that largely mimics the regression coefficient map shown in Figure 1b. For example, Healy (2003) identified the United Kingdom as one of the countries with largest seasonal variation (i.e. winter vs. other seasons) in mortality, together with the neighboring Ireland and the southern countries of Portugal, Spain, Italy and Greece (cf. with Figure 1b). Healy (2003) determined several explanatory factors of the comparatively large incidence of winter mortality in these countries: parity adjusted per capita national income, per capita health expenditure, rates of income poverty, inequality, deprivation and fuel poverty and several indicators of residential thermal standards. The Eurowinter Group (1997) also found similar results in spatial covariance for the same countries, pointing to factors such as low living-room temperatures, limited bedroom heating, low proportions of people wearing hats, gloves and anoraks, and inactivity and shivering when outdoors at 7°C.

The different spatial distribution shown in these studies, which is here generalized and provided in further detail in Figures 1a,b, poses an apparent contradiction: if the vulnerability of a society to cold days increases with decreasing temperatures, should not this society be more sensitive to years with harsh winters compared to milder winters? In other words, are large (small) day-to-day regression coefficients compatible with small (large) year-to-year correlations in a given city, region or country? A theoretical solution to this dilemma is schematically proposed in Figure 3, in which the probability distribution function of daily temperatures and the temperature/mortality relationship are shown in red and dark blue, respectively. During colder-than-normal winters ($\Delta T < 0$), the society might take actions in order to stop or damp the subsequent increase in seasonal mortality, which is here expressed through the translation of the temperature/mortality relationship along the temperature axis (ΔR, with $\Delta T \leq \Delta R \leq 0$). The larger is the response to these adverse environmental conditions, the larger will be the degree of acclimatization of the society at interannual timescales (α, with $\Delta R \approx \alpha \cdot \Delta T$). Note that the level of vulnerability to cold seasonal temperature anomalies ($0 \leq 1 - \alpha \leq 1$, cf. with Figure 1a) is not conceptually related with the degree of sensitivity to cold temperature days ($\beta = \partial M / \partial T$, Figure 1b). For example, in the United Kingdom, year-to-year correlations are small (i.e. small vulnerability to cold seasonal anomalies, or $1 - \alpha \approx 0$) and day-to-day regression coefficients are large (i.e. large sensitivity to cold temperature days, or large β), while the opposite situation is found in many countries in central Europe (e.g. Switzerland, with $1 - \alpha \approx 1$ and small β, cf. Figures 1a,b).

The α coefficient represents the adaptation response of the society to year-to-year temperature fluctuations, but an analogous acclimatization mechanism is found at longer timescales. Climatological and comfort temperatures are strongly associated, so that the colder is the climate in a region the colder is also the temperature at which citizens experience the lowest temperature-related mortality rates (r = 0.87; Figures 2a,b). The spatial regression coefficient of this nearly linear relationship is however lower than 1, i.e. a decrease of 2°C in winter mean temperature is associated with a decrease of 1°C in the comfort temperature (r = 0.69, Supplementary Figure 3). As a result, the difference between comfort and annual mean temperatures is negatively correlated with both the climatological base state and the temperature of minimum mortality (cf. Figures 2a,b with Figure 2c). These relationships suggest that human populations exposed to cold background temperatures have experienced a long-term acclimatization process, where $\Delta R' \approx \alpha' \cdot \Delta T$ represents the spatial dependency between winter mean (T) and comfort (R') temperatures. The fact that the α' coefficient is lower than 1 (i.e. $\alpha' \approx 0.5$, Supplementary Figure 3) suggests that this long-term adaptation scheme might be partially constrained by mechanisms linked to human physiology and/or the natural dynamics of the pathogens associated with the seasonal rise of mortality in winter. Nonetheless, this incomplete acclimatization process seems to be somehow complemented by the decreasing values of the day-to-day regression coefficients with latitude (i.e. Figures 1b,2c are negatively correlated in space).

The different, and apparently contradictory, spatial distribution of human vulnerability to year-to-year and day-to-day winter anomalies (i.e. Figures 1a,b) has become a central topic of intense ongoing scientific debate, which is especially vivid in the particular case of the United Kingdom. SMD14 analyzed data from December to March to show that the year-to-year association between excess winter deaths and winter temperatures has declined during the last 6 decades, concluding that there is no evidence that excess winter deaths will fall if winters warm with climate change. Hajat and Kovats (2014) responded that the analysis of SMD14 was flawed because the excess winter deaths are an inappropriate metric for the evaluation of health impacts associated with either current or future climate, and because cold-related mortality is not restricted to the December-March period. Nonetheless, our analyses are not based on excess winter deaths, but they still confirm the main result of SMD14 for the United Kingdom (i.e. year-to-year correlation of -0.12, Table 1). Additional analyses were performed in order to show that results remain unchanged when correlations are computed for the cold half of the year, regardless of the period of months used for the calculations (i.e. year-to-year correlation of -0.11, Supplementary Table 1).

Here we conclude that this intense scientific debate simply stems from a misleading comparison between apples and oranges, that is, between types of acclimatization that are conceptually different and cannot be compared. On the one hand, in the light of the declining year-to-year association between excess winter deaths and winter temperatures in England and Wales (cf. with Figure 1a), SMD14 concluded that many of the studies describing a significant association in economically developed societies such as Europe, Canada and the United States were correct on the basis of old data available a couple of decades ago, while more recent studies are either inconclusive or show a weak relationship. The studies cited by SMD14 (please find the references therein) however generally describe the increase in the odds of death for a 1°C decrease in daily winter temperatures, which is equivalent to the methodology used in Figure 1b. In addition, our Figure 1a contradicts this generalization by showing that year-to-year correlations are still large in most of the countries in western Europe, representing the 81% of the analyzed population. On the other hand, Hajat and Kovats (2014) used the supplementary material of Bennett et al. (2014) (see Supplementary Figures S4 and S5 therein) as a counterexample to the results of SMD14 for the United Kingdom. However, the methodology used in Bennett et al. (2014) is equivalent to the day-to-day regression coefficient map shown in Figure 1b, while the analysis in SMD14 is completely based on year-to-year correlations (cf. with Figure 1a).

Our study characterizes the spatial variability associated with the degree of acclimatization of the European society to cold winter temperatures at interannual and intraseasonal timescales, providing for the first time a detailed picture of current human vulnerability at the regional level. Strikingly, Figures 1a,b show that the degree of exposure to cold temperatures is different at different timescales, suggesting that a society that remains particularly sensitive to cold extreme days can take actions in order to decrease and eliminate the seasonal vulnerability to harsh winters, and vice versa. Nonetheless, the future evolution of temperature-related mortality will be both determined by the temperature/mortality relationship, which is largely characterized by the slope in each tail (e.g. β coefficient in Figure 3) and the capacity of acclimatization of the society to increasingly warmer year-to-year temperature anomalies (α coefficient in Figure 3). Although the spatial distribution and future evolution of the degree of exposure to both year-to-year and day-to-day variability are key to infer the contribution of climate change to future projections of mortality (Figures 1a,b), very few studies have considered the combined effect of these two factors. McMichael et al. (2006) was the first to propose a conceptual framework with decreased mortality rates in the warm tail, expressing the acclimatization to warm temperatures as climate warms, which was subsequently generalized by Ballester et al. (2011) to infer the long-term projection of future annual mean mortality under scenarios of acclimatization to warm and/or cold temperatures.

Given the different nature and spatial distribution of human exposure to these two phenomena, here we propose an index that integrates the vulnerability associated with cold days and harsh winters. This index of sensitivity to cold temperatures is defined as the product (with reversed sign) of the year-to-year correlation and the day-to-day regression coefficient (see Methods). Note that the index is close to zero if the response of the society to adverse seasonal temperatures is large (i.e. small year-to-year correlation, or $\alpha \approx 1$ in Figure 3) and/or the slope of the temperature/mortality relationship is small (i.e. $\beta \approx 0$ in Figure 3). The index is found to be small in the Netherlands, Belgium and the United Kingdom (0, 0 and -0.05 daily cases/million/°C, respectively), and large in the southern countries of Portugal, Spain and Italy (-1.09, -0.60 and -0.50 daily cases/million/°C; Table 1c). The other countries, ranging from Denmark (-0.12 daily cases/million/°C) to Austria (-0.23 daily cases/million/°C), are shown to exhibit intermediate values. Strikingly, the index is shown to integrate the large capacity of adaptation to interannual anomalies in winter mean temperature observed in the Netherlands, Belgium and the United Kingdom with the latitudinally-oriented distribution of vulnerability to cold days and extremes (cf. Figures 1a-c).

In conclusion, Figure 1 suggests that climate warming will decrease winter mortality in most of the countries in western Europe. Does this mean though that the European society has to simply wait and embrace the steady increase in global temperatures without taking actions in order to mitigate this change or at least to adapt to its negative impacts? In this sense, European citizens will remain largely exposed to the natural fluctuations in daily and/or seasonal winter temperatures. In addition, Ballester et al. (2011) showed that heat-related mortality will start to completely compensate the reduction of deaths from cold during the second half of the century, unless a substantial degree of adaptation to warm temperatures takes place. In that regard, our unprecedented characterization of the different types of human acclimatization will prove useful for a better understanding of the adaptation measures so far implemented in some countries, in order to be generalized also in those societies that are still vulnerable to environmental cold temperatures.

Methods

Daily regional counts of mortality from 1 January 1998 to 31 December 2005 were collected for 16 European countries representing around 405 million people. These countries are Austria, Belgium, Croatia, the Czech Republic, Denmark, France, Germany, Italy, Luxembourg, Netherlands, Poland, Portugal, Slovenia, Spain, Switzerland and the United Kingdom (England and Wales only). Daily high-resolution (0.25° × 0.25°) observations and A1B greenhouse gas emission scenario simulations (25x25 km^2) of daily mean 2-meter temperature were derived from E-OBS v10 (Haylock et al. 2008) and the ENSEMBLES project (Jacob et al. 2008), respectively. Observational and simulated gridded datasets were interpolated to the regional level by taking into account the higher population density in cities and metropolitan areas. The time lag between temperature and counts of deaths was chosen in order to maximize the amount of explained variance: unlagged for summer (June-September, Keatinge et al. 2000) and 1 week for autumn, winter and spring (October-May, Kunst et al. 1993). The combined index of vulnerability was defined as $-min(c,0)\cdot r$, where c represents the year-to-year correlation between winter mean temperature and mortality (unitless) and r the regression coefficient between daily temperature and mortality for winter days (in daily cases/million/°C).

Acknowledgements

J.B. gratefully acknowledges funding from the European Commission through a Marie Curie International Outgoing Fellowship of the 7th Framework Programme for Research (project MEMENTO from the FP7-PEOPLE-2011-IOF call). X.R. acknowledges funding from the EUFP7 project EUPORIAS. We acknowledge the ENSEMBLES project, funded by the European Commission's 6th Framework Programme through contract GOCE-CT-2003-505539. The mortality data collection was supported by the EU Community Action Programme for Public Health (Grant Agreement No. 2005114).

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Contributions

J.B. took the lead role in the design of the study, analyzed the data and wrote the manuscript. X.R. contributed to the discussion of results and to the revision of the manuscript. F.R.H. and J.M.R. collected the set of daily regional numbers of deaths.

Competing financial interests

The authors declare no competing financial interests.

Country	a. Year-to-year correlation	b. Day-to-day regression coefficient	c. Combined index of vulnerability
Portugal	-0.97	-1.13	-1.09
Spain	-0.88	-0.67	-0.60
Italy	-0.96	-0.52	-0.50
Austria	-0.96	-0.24	-0.23
Czech Republic	-0.88	-0.25	-0.22
Croatia	-0.97	-0.23	-0.22
France	-0.83	-0.26	-0.22
Slovenia	-0.93	-0.20	-0.19
Luxembourg	-0.81	-0.17	-0.14
Germany	-0.85	-0.16	-0.13
Switzerland	-0.88	-0.15	-0.13
Poland	-0.70	-0.18	-0.13
Denmark	-0.60	-0.21	-0.12
United Kingdom	-0.12	-0.38	-0.05
Belgium	0.38	-0.22	0.00
Netherlands	0.08	-0.14	0.00

Table 1. Human vulnerability to winter (DJFM) temperatures at the country level.
(a) Year-to-year correlation between winter mean temperature and mortality. (b) Regression coefficient between daily temperature and mortality for winter days (daily cases/million/°C). (c) Combined index of vulnerability to winter temperatures (daily cases/million/°C).

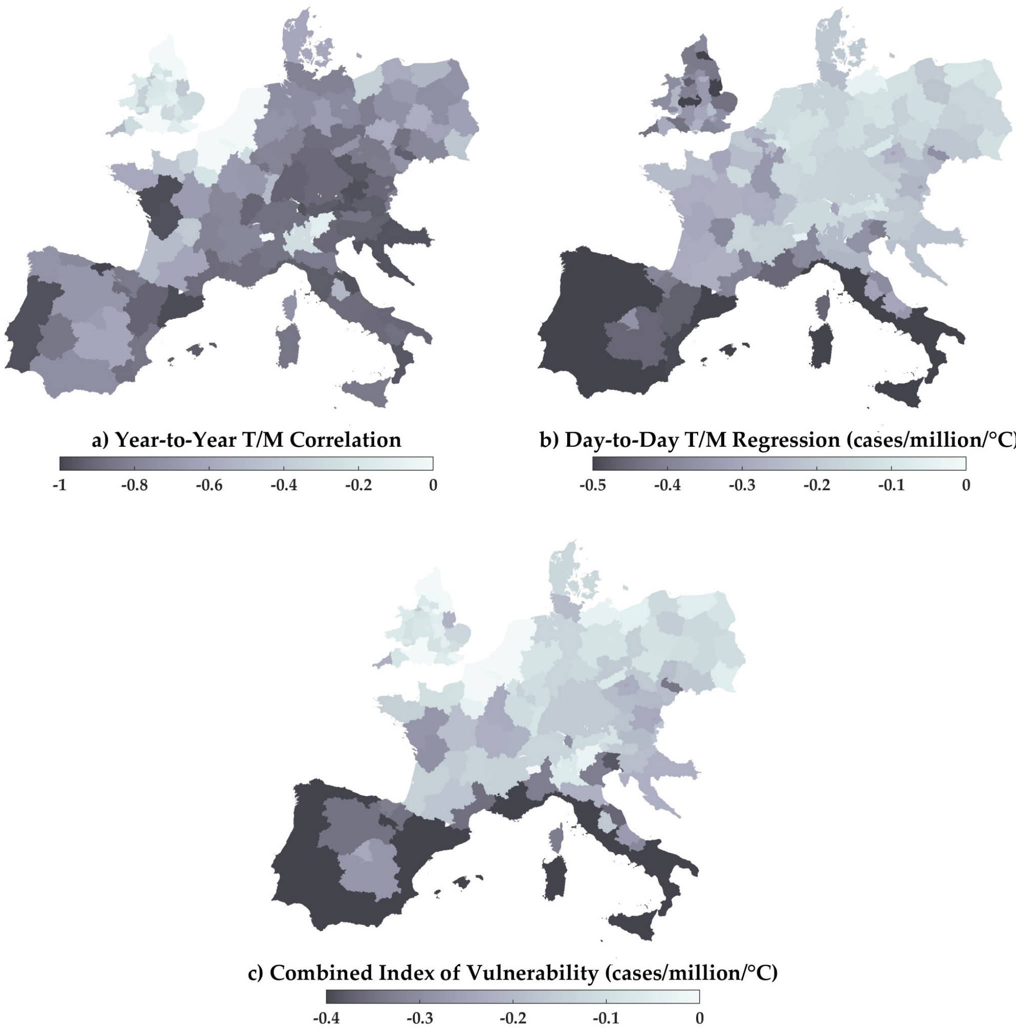


Figure 1. Human vulnerability to winter (DJFM) temperatures at the regional level. (a) Year-to-year correlation between winter mean temperature and mortality. (b) Regression coefficient between daily temperature and mortality for winter days (daily cases/million/°C). (c) Combined index of vulnerability to winter temperatures (daily cases/million/°C).

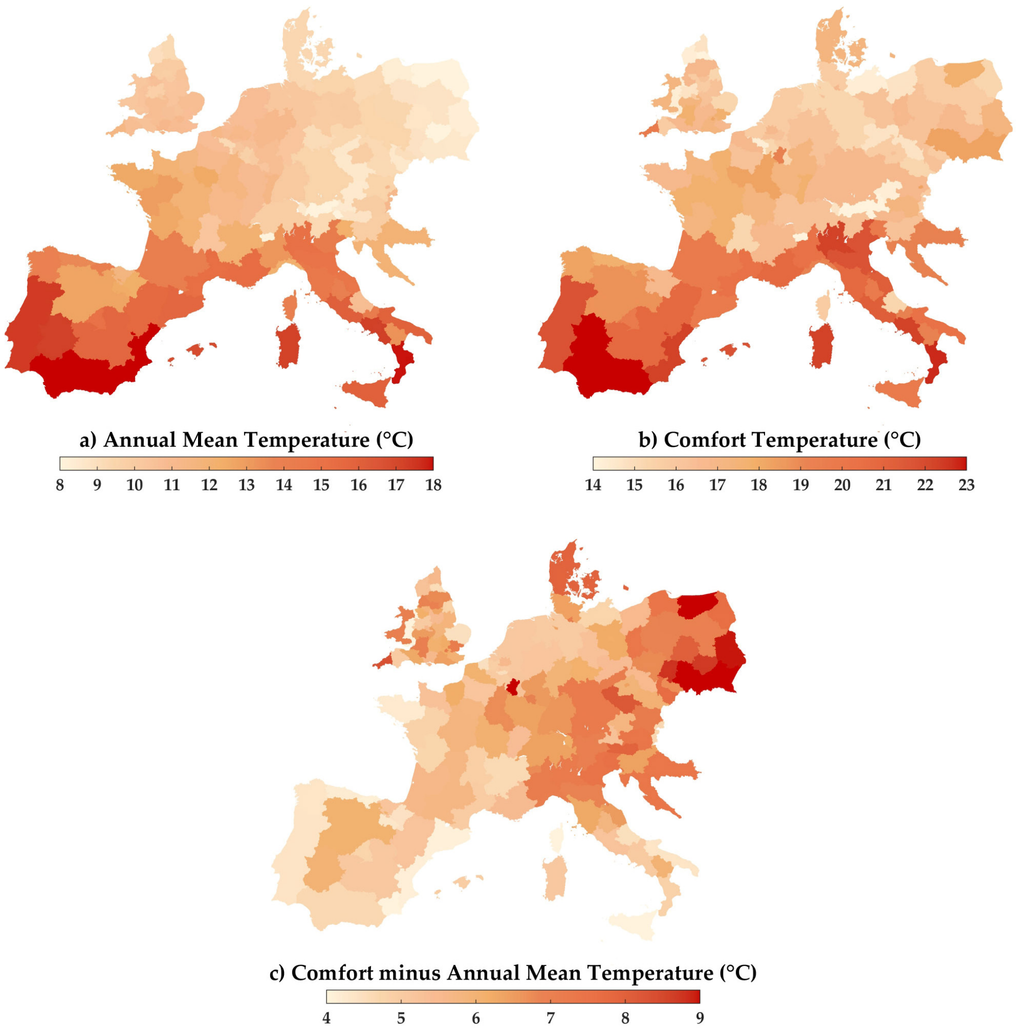


Figure 2. Annual mean (a) and comfort (b) temperature (°C).

Panel c shows the difference between comfort minus annual mean temperature (°C).

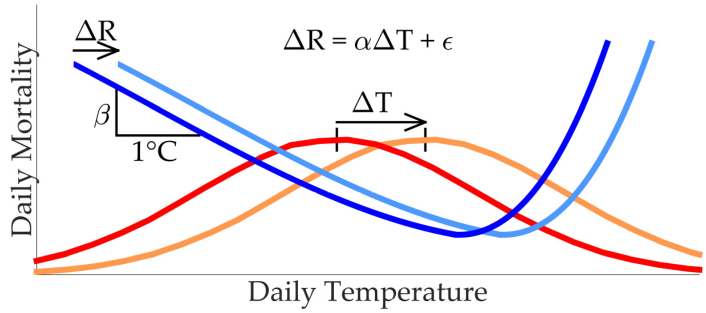
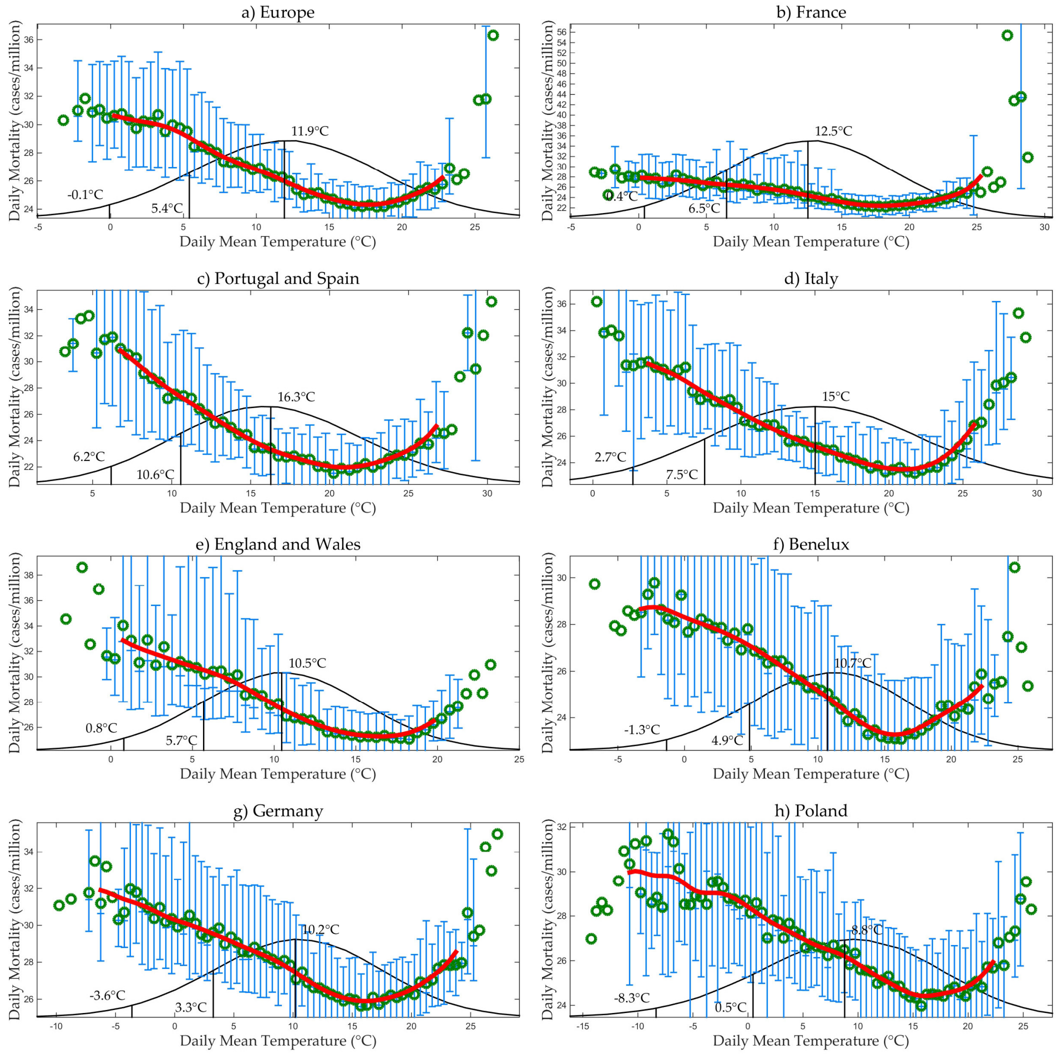


Figure 3. Schematic representation of human adaptability.

The probability distribution function of daily temperatures and the daily temperature/mortality relationship are shown in red and dark blue, respectively. Year-to-year anomalies in the temperature probability distribution function (ΔT) and the temperature/mortality relationship (ΔR) are represented in orange and light blue, respectively. The societal response to interannual temperature anomalies is expressed as $\Delta R = \alpha \cdot \Delta T + \varepsilon$, where $0 \leq \alpha \leq 1$ is the degree of adaptability of the society and ε is a non-temperature-related zero-mean noise process. Note that the level of vulnerability to cold seasonal temperature anomalies ($0 \leq 1 - \alpha \leq 1$, cf. with Figure 1a) is not directly related with the degree of sensitivity to cold temperature days ($\beta = \partial M / \partial T$, Figure 1b).

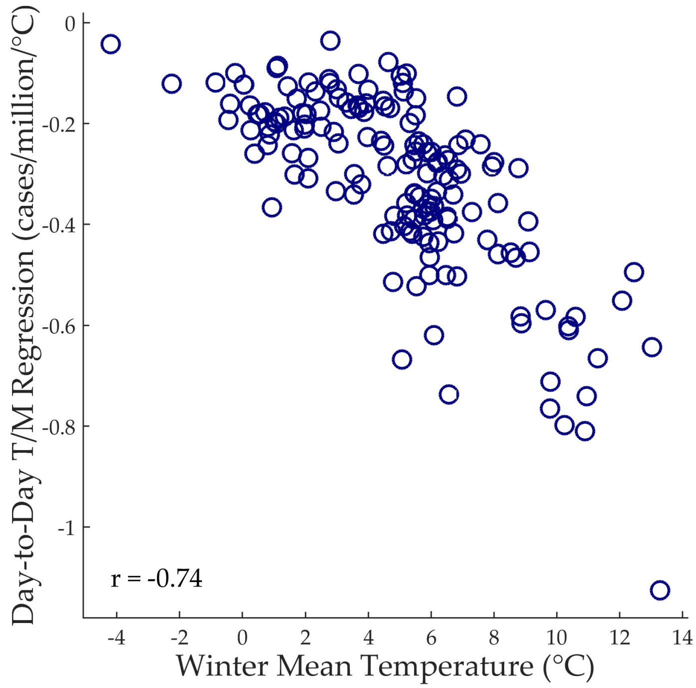
Country	a. Year-to-year correlation	b. Day-to-day regression coefficient	c. Combined index of vulnerability
Portugal	-0.92	-1.34	-1.23
Spain	-0.78	-0.74	-0.58
Italy	-0.82	-0.59	-0.49
Austria	-0.93	-0.30	-0.28
Czech Republic	-0.94	-0.29	-0.27
Croatia	-0.82	-0.33	-0.27
France	-0.86	-0.26	-0.22
Slovenia	-0.71	-0.23	-0.17
Luxembourg	-0.95	-0.23	-0.22
Germany	-0.82	-0.25	-0.20
Switzerland	-0.65	-0.24	-0.16
Poland	-0.88	-0.22	-0.19
Denmark	-0.33	-0.35	-0.12
United Kingdom	-0.11	-0.56	-0.06
Belgium	0.29	-0.36	0.00
Netherlands	-0.15	-0.22	-0.03

Supplementary Table 1. Human vulnerability to cold temperatures at the country level. Values are computed for the ensemble of days colder than percentile 50 of the temperature probability distribution function (i.e. cold half of the year), regardless of the month. (a) Year-to-year correlation between winter mean temperature and mortality. (b) Regression coefficient between daily temperature and mortality for winter days (daily cases/million/°C). (c) Combined index of vulnerability to winter temperatures (daily cases/million/°C).

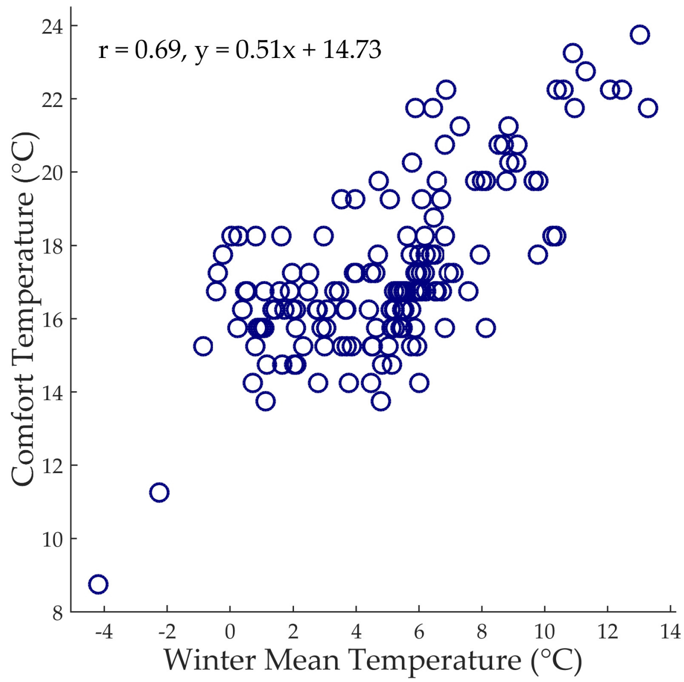


Supplementary Figure 1. Relationship between daily temperature and mortality for winter (DJFM) days.

The temperature/mortality relationship (°C vs. daily cases/million) is shown for Europe (a), France (b), Portugal and Spain (c), Italy (d), England and Wales (e), Benelux (f), Germany (g) and Poland (h). Green circles correspond to temperature and mortality averages of daily data within equally-spaced temperature intervals, and blue vertical lines to the 90% confidence interval of daily mortality. Red curves show the running average of interval mean temperature and mortality daily data.



Supplementary Figure 2. Relationship at the regional level between winter mean (DJFM) temperature (x-axis, °C) and the regression coefficient between daily temperature and mortality for winter days (y-axis, daily cases/million/°C).



Supplementary Figure 3. Relationship at the regional level between winter mean (DJFM) temperature (x-axis, °C) and comfort temperature (y-axis, °C).