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Expert judgement reveals current and emerging UK climate-mortality burden

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Weather and climate patterns play an intrinsic role in societal health, yet a comprehensive synthesis of specific hazard–mortality causes does not currently exist. Country-level health burdens are thus highly uncertain, but harnessing collective expert knowledge can reduce this uncertainty, and help assess diverse mortality causes beyond what is explicitly quantified. Here, surveying 30 experts, we provide the first structured expert judgement of how weather and climate directly impact mortality, using the UK as an example. Current weather-related mortality is dominated by short-term exposure to hot and cold temperatures leading to cardiovascular and respiratory failure. We find additional underappreciated health outcomes, especially related to long-exposure hazards, including heat-related renal disease, cold-related musculoskeletal health, and infectious diseases from compound hazards. We show potential future worsening of cause-specific mortality, including mental health from flooding or heat, and changes in infectious diseases. Ultimately, this work could serve to develop an expert-based understanding of the climate-related health burden in other countries.

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Introduction

Causal pathways of changes in human health with weather and climate patterns can be clear and direct, for instance storm-related injuries or deaths such as impact trauma from debris or drowning during a flash flood. However, other health outcomes have more complex causal pathways so are not as easy to attribute, especially when the response does not immediately follow exposure. For instance, during consecutive days of excessively high temperatures, heat stress can cause a physiological response that can overwhelm the body's thermo-regulatory systems, especially in older people with underlying health conditions.[1–3] Here, the exposure response will not be instantaneous, but might still be fast (eg, hours or days). There are examples where the exposure might need to be considerably longer (even decades)—for instance, related to sleep disorders from excess heat or trauma-induced insomnia.[4] Weather and climate patterns might also impact health via a mediator;[5] for example, ticks in the UK might emerge earlier in the season if the spring is particularly warm resulting in the enhanced spread of tick-borne diseases, such as Lyme disease.

Understanding the links between weather hazards and the plethora of associated health impacts in today's climate and projecting how they could develop in a changing climate is important to inform climate change adaptation and increase resilience, which is especially true given the degree to which record shattering extreme events are occurring.[6–8] Major European[9] and UK[10,11] climate-health reports monitor and project the trends in quantifiable weather-related health outcomes over time, but do not necessarily include health outcomes with links to weather that are less immediately apparent, or outcomes that develop because of long-term exposure to weather hazards among multiple other causes. Some of these reports also do not anticipate new outcomes that are not prevalent at present, but could emerge in future. This knowledge gap in the literature is challenging to fill with quantitative modelling alone, as doing so would require long-term observational records and a wide range of climate-health models that do not exist yet, and trust in these models that are outside of the sample. Currently, most assessments of weather and climate risks utilise process-based models, often with a core grounding in the physics of the earth system. These models can be combined with statistical-based models that translate the output into the health risk being considered. Given the complexity of the climate and health nexus, it is unsurprising that existing model-based estimates and uncertainties of climate-related mortality might be substantially biased, which is especially true when dealing with climate extremes, because climate models are known to miss or inadequately resolve important processes, such as the urban heat island effect. As these extremes could have the highest health impact and their estimates tend to be conservative, we should pay special attention to them.[12]

A powerful way to overcome this challenge is to use structured expert judgement (SEJ), which allows for a holistic view of the multifaceted topic about the extent to which climate change could increase mortality from specific diseases or injuries. SEJ utilises experts in climate impacts, health modelling, and clinical research who have a vast knowledge and experience that allows professional assessments of relative changes in weather-health risks, notwithstanding limited data or specific models. Expert judgement has been widely used in other disciplines such as nuclear risks or volcanology.[13] Formalisation of expert judgement ranges considerably in complexity, from a single individual's opinion, to formal elicitation and external validation,[13] and has been used in large climate reports, such as those of the Intergovernmental Panel on Climate Change (IPCC) to help constrain climate sensitivity.[14] Expert

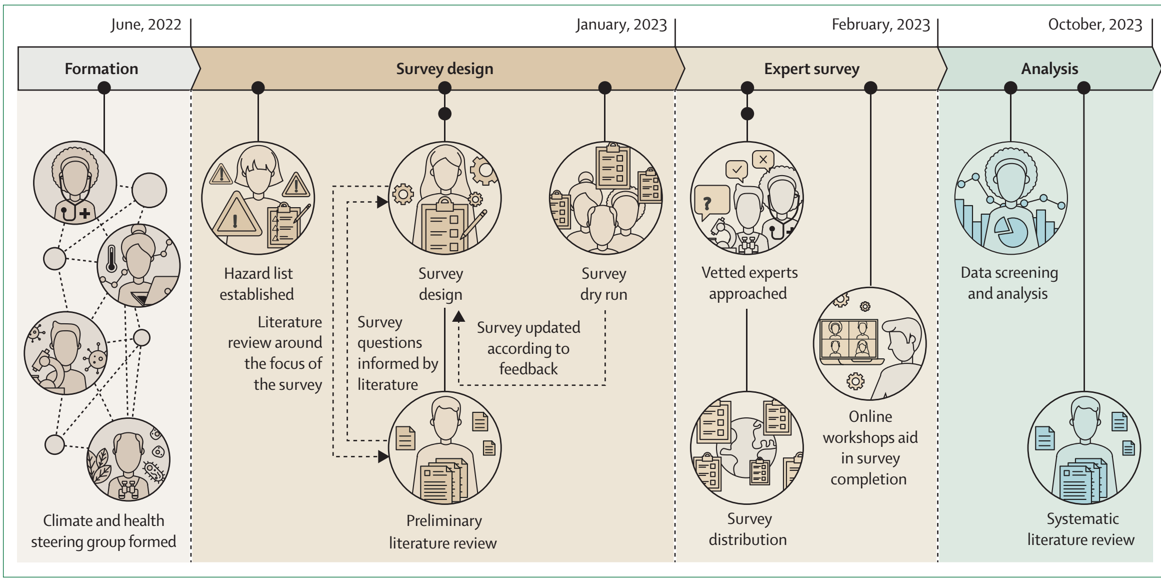

Figure 1: **The study design and timeline of the structured expert judgement**

	Description of cause	Most susceptible age (years)
Heat and drought		
Drowning	Drowning from swimming during good weather	5–65
Cardiovascular disease	Heat stress leading to stroke or heart attack from dehydration, vasodilation and hypotension, electrolyte disturbance, etc.	>65
Respiratory disease	Cardiovascular pressure changes on the respiratory system during exposure to extreme heat, or bronchoconstriction leading to exacerbation of respiratory conditions; air quality factor changes (eg, ozone) during high temperatures	>65
Mental health	Change in mental health resilience; suicide and stress leading to violence (eg, domestic or alcohol); stress leading to accidents (eg, motor vehicle accident); changes in risk-taking behaviour; delirium	5–65
Sleep disorders	Sleep disruption; disturbance of sleep cycle (eg, reduced rapid-eye movement sleep); associated cognitive decline (eg, Alzheimer's disease)	>65
Renal disease	Dehydration leading to inefficient kidney function and poor regulation of water and salt balance	>65
Skin cancer	Change in skin cancer prevalence due to being outdoors in nice weather more and changes in cloud cover (not due to ultraviolet change from ozone depletion)	>65
Cold		
Ice-related trauma	Trauma from accidents involving ice (eg, slipping or motor vehicle accidents)	5–65, >65
Mental health	Change in mental health resilience (eg, isolation)	5–65, >65
Musculoskeletal health	Reduced physical activity; chronic pain (eg, weather-related joint pain)	5–65, >65
Cardiovascular disease	Cold stress leading to stroke or heart attack from hypothermia, metabolic disturbance, etc.	>65
Respiratory disease	Due to seasonal respiratory infections (eg, influenza A or B, SARS-CoV-2, respiratory syncytial virus, etc); inhalation of particulate matter and other air quality factors during cold temperatures	>65

(Table continues on next page)

judgement has also proved to be particularly useful for constraining sea level projections,[15–17] for understanding risk from different health system interventions,[18] and quantifying the social cost of carbon (of which mortality is one part).[19]

Here, we present an expert elicitation based on the opinions of 30 experts from environmental and health disciplines. To our knowledge, our study is the first to take this approach to understand the complexities, contributions, and uncertainties associated with the role that weather and climate change play on all different causes of mortality. Given that weather and climate hazards influence population health in different ways for each country around the world, it is most meaningful to start with a single country with the aim that such a methodology could be expanded to include other countries as the techniques become more mature. We selected the UK as an example because it has a large peer-reviewed evidence base of weather and climate-health research compared with most other countries, along with well validated and open meteorological and health data. Within the UK, there is a range of weather and climatic conditions ranging from the cold, moist air intrusions in Northern Ireland and the West of Scotland, to advection of hot dry air-masses to Southern England from lower latitudes (called Spanish plumes). The response of society to these conditions (ie, the social vulnerability) is also spatially inhomogeneous, from the country scale to the neighbourhood scale. For instance, each of the devolved nations of the UK are responsible for their own branch of the National Health Service, which can lead to differences in vulnerability within their populations. Indeed, expert elicitation methods have been used in other countries to study how population vulnerability to environmental hazards changes from differing socioeconomic conditions—eg, in the region of Aragón (Spain) by consulting with regional experts that have knowledge on a range of local emergency response plans.[20] Another example is in Helsinki (Finland) where urban heat island experts assess the level of consensus and certainty in a given vulnerability change.[21] A similar methodological approach has also been used in Taiwan, which suggested that social resources and support were a leading cause of heat-vulnerability in their country.[22] This level of spatial detail and vulnerability is not captured in our study as our complexity is focused on physical hazard–mortality pathways, rather than individual vulnerabilities.

SEJ is a particularly useful tool for our framing because different research tools often lead to disagreement, especially on the upper tail of the climate-health burden.[23] This type of problem lends itself particularly well to SEJ.[13] Our results are important to: (1) identify the dominant meteorological and disease or injury causes of mortality in the UK in the present-day climate, (2) assess uncertainties in these causes, (3) highlight underappreciated areas in the climate and health nexus, and (4) anticipate serious health threats that could emerge in the future due to climate change. Our study sets a precedent for similar expert elicitation studies in other countries, where weather hazards and health vulnerabilities are expected to be different, and in many cases higher, than those of the UK.

	Description of cause	Most susceptible age (years)
(Continued from previous page)		
Storms and flooding		
Lightning and electrocution	Electrocution by lightning strike	5–65
Trauma from weather and debris	People falling over due to increased rain or wind (especially more frail people), or debris caused by high winds (eg, falling trees and roof tiles)	>65
Drowning	Drowning from flooding, storm surge, waves, or a combination of all	5–65, >65
Mental health	Suicide; stress leading to violence (eg, domestic or alcohol); stress leading to accidents (eg, motor vehicle accident); population displacement; post-traumatic stress disorder	5–65, >65
Water-borne disease	Flood induced water pollution, overflowing sewage, and other systems (eg, *Escherichia coli*)	<5, 5–65, >65
Radiation sickness	Radiation contaminated water from flooding of radioactive infrastructure	<5, 5–65, >65
Wildfire		
Burns	Direct exposure to fire causing extreme burning	5–65, >65
Respiratory disease	Respiratory exposure to particulate matter from sudden or persistent burning of vegetation	<5, >65
Compound		
Infectious disease	Contraction of a tick or mosquito-borne, bacterial or viral disease, which considerably shortens life	<5, 5–65, >65
Allergy	Respiratory and cardiovascular exposure to allergens (eg, asthma or mould) from changes in weather patterns (eg, wind, temperature, humidity, lightning, thunderstorms, or dust)	5–65, >65

The susceptibility age was established from the systematic literature review (appendix 1 p 3), and represents the age group (or groups) with the largest overall susceptibility to the health outcomes listed within the description. We define three age groups (age <5, 5–65, and >65 years).

***Table:* Definitions of the health outcomes from UK weather and climate hazards, as given to the survey participants**

Methods

An overview of the method timeline is given in figure 1, with the individual components explained in the text. Our method can be broadly divided into three parts: survey design, survey completion, and analysis.

Establishing the survey design

The survey design was an iterative process, which began by identifying the relevant weather and climate hazards using the UK National Risk Register as a primary guide.[24] From this, our steering group defined five categories relevant for UK health, but note that other equally defensible typologies could be formed. The five categories were: heat and drought, cold, storms and flooding, wildfire, and compound climate that encompasses multifaceted environmental conditions that favour the spread of infectious diseases or allergens. Using ticks in the UK as an example, in addition to a temperature dependence, ticks thrive under higher humidity and more precipitation, hence the spread of tick-borne diseases falls under the compound climate hazard category. A list of how all five hazards can lead to different health outcomes is given in the table.

By preliminary review of the literature and expert consultation with the survey steering committee, we developed an initial list of the clinical pathways where these different weather and climate patterns in the UK could potentially lead to mortality (table). As with the hazard typology, different equally defensible ways of grouping these hazard-health links are also possible. This list excludes anything from outside of the UK, which would have a link to health within the UK. For example, the weather and climate effects on food imports due to drought-related failure of the major breadbaskets from around the world,[25] or climate-related conflict and migration due to restricted access to resources.[26] Such external factors could cause health burdens for the UK, and feature in the UK National Risk Registry.[24]

See Online for appendix 1

The established list of hazards and health pathways was then checked by a range of clinical experts who would not be involved in the survey completion. They were all asked specific questions on their area of expertise, but one (CLG) expert was also asked to review the complete list, including the likely relevant temporal exposures needed to lead to mortality and the most susceptible age category for each health outcome. The final list of hazards and health pathways is given in the table. This table informed the creating of the survey, which involved a number of dry runs with colleagues at the University of Bristol who were not involved in

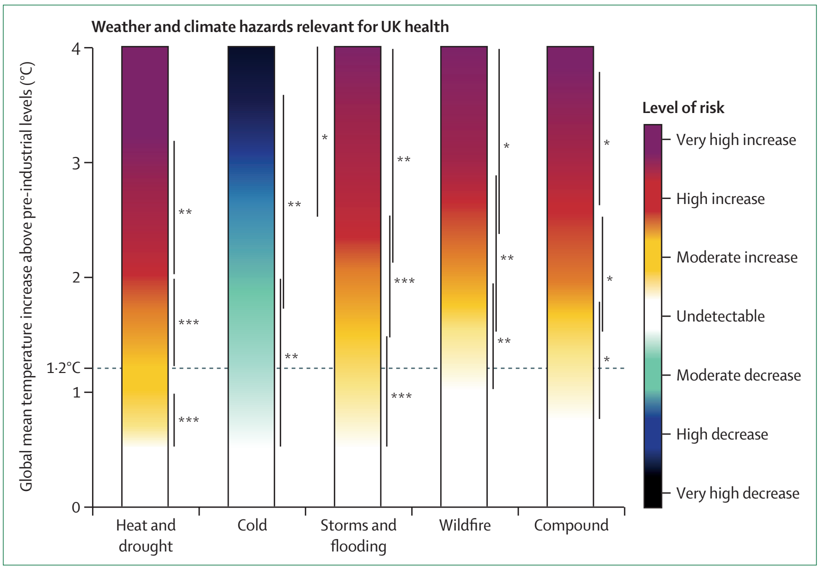

***Figure* 2. Synthetic diagrams of weather and climate hazards that drive mortality in the UK**

The x axis shows the relevant hazards. The y axis shows the global mean temperature level relative to pre-industrial levels (1850–1900), with the 2022 annual global mean temperature (1·2°C) marked with a dashed line. The colours show how the risks associated with each hazard increase or decrease as the climate warms. The vertical lines give the range of possible transitions, calculated from the spread in survey responses, and are an indicator of the uncertainty among participants. The asterisks show the number of participants answering each question, with fewer dots indicating that there were not many experts who felt confident enough to offer a judgement on that particular risk transition. One dot represents less than a third of the participants, two dots represent between a third and two-thirds, and three dots represent more than two-thirds. Risk was evaluated at the national population level, and might be different for individual communities. The methods behind calculating the transitions and uncertainty are given in appendix 2 (p 1).

See Online for appendix 2

the study, but were experts in survey design and structured expert judgements. These external, independent review safeguards were put into place to reduce any bias associated with the author team unconsciously focusing on specific topics.

Completing the expert survey

We approached 102 experts to complete a series of questions about UK weather-related and climate-related health, and around a third of them formally committed to the workshop and survey activities. The questions that were asked are given in appendix 2 (pp 7–13). The experts were vetted ahead of time and chosen because of their relevant research in environmental science (ten [33·3%] of 30 identified to be in this category), 12 (40·0%) for environmental science with a secondary focus on health, seven (23·3%) for health science with a secondary focus on environmental science, or one (3·3%) for health science (appendix 2 p 5). All experts have either published four or more relevant peer-reviewed papers in their respective field within the last 5 years or are early career researchers who are doing a relevant PhD. These experts came from 15 institutions (appendix 2 p 6) mostly from the UK. We ensured that our pool of experts covered all hazards listed in table and had a range of geographical foci spanning the devolved administrations of the UK. We included numerous calibration questions in the survey, which the experts needed to answer correctly to be considered (appendix 2 pp 10–11). After calibration, there were 30 participants whose answers were included in the analysis. While in classical uncertainty analyses used in climate, health, and many other fields, 30 might be considered a small sample size, but here it is large. The goal of a structured expert judgement is not to survey the distributions of opinions in a population where a sample of 30 would often be deemed inadequate, but rather to sample a highly vetted set of experts. For example, a review of 49 structured expert judgements found that the average sample size was 11 experts, and the study with the highest number had 58 experts.[27]

Participant names were kept anonymous throughout the analysis for ethical reasons, but many opted to disclose their contribution to this paper. The names of these experts and their institutes are given in appendix 2 (p 6). Five of the experts who helped create the list of hazards and health outcomes are authors of this paper. All conclusions in this study were based on the numerical values input by the collection of experts, so having authors who are also survey participants should not bias the results.

The survey, containing all the questions presented in this study, was sent out in January, 2023 and asked the experts about the global mean temperatures that they expect would risk transitions for the five UK weather and climate hazards relevant for health. For instance, the first risk transition would be classed as the global mean temperature at which a moderate increase in health burden from each of the five hazards was detected. The next section asked the experts about the current mortality burden from specific mortality causes, and how that would change by 2100 under a likely future climate change scenario. Experts only answered questions that they felt they were qualified to do so (response numbers are given in appendix 2 p 2).

The experts were asked to complete the survey within 4 weeks of receiving the survey invitation email. When the survey was initially sent out, experts were invited to a set of optional online workshops where the scope of the survey was discussed and its aims clarified. These were 1 h sessions, once a week, for the 4-week survey period. The survey itself was completed privately by each expert. Of note, we did not run in-person workshops, as in other structured expert judgements, due to the concern regarding the ongoing COVID-19 pandemic at the time.

All responses were anonymised by the project manager before any analysis was performed. We gave all responses equal weights as opposed to performance-based weights, as the range of questions being asked in our survey would have made performance-based weights complex to interpret.[28] Both types of weighting system generally result in improved statistical accuracy,[13] but the performance-based system (where possible) often outperforms the equal-weight system.[29]

To create the main synthesis figures for this study, specific methodological choices were made to combine all answers—eg, when assessing the most common response or the level of consensus (appendix 2 p 1). The survey data are available in appendix 1 and appendix 3.

See Online for appendix 3

Systematic literature review

To ascertain the number of peer-reviewed studies on each of the health outcomes in the literature, multiple reviews were undertaken using the PRISMA guidelines for systematic reviews.[30] Keyword searches were performed in the Web of Science and Scopus databases for each of the weather and climate hazards and associated health outcomes within the UK, along with a separate search for all-cause mortality related to each hazard. For individual health outcomes, articles on morbidity were included alongside mortality since for some outcomes there is no published work investigating mortality, but there is a body of literature investigating the link between hazard and morbidity. Full inclusion and exclusion criteria are given in appendix 2 (pp 2–4). Information, the search terms, and the number of articles included or excluded at each stage of the review are given in appendix 2 (p 4), along with a full bibliography of included articles.

Results

Changing hazards in a warmer climate

An important communication tool to show the changes in risks attributable to different levels of global warming is the use of synthetic diagrams (informally known as burning embers diagrams), which are widely developed and used in the IPCC, especially Working Group 2.[31] We used these synthetic diagrams for our five UK-relevant health-hazard categories, assuming limited investment into UK health systems in the future (figure 2). To our knowledge, this is the first time a complete set of health-relevant hazards was synthesised for a specific country, although other collections that focus on the leading health burdens of continents and health system interventions have been developed.[18,31] Our analysis shows that rising global mean temperatures are expected to result in increased risk for all major UK hazards relevant to health, excluding cold temperatures. There was consistency between our assessment of UK heat and drought-related health risk transitions (figure 2) and that of the latest IPCC reports. For instance, the IPCC Working Group 2 has similar graphics for Europe,[32] and for the globe as a whole (supplementary figure SPM.3e).[31] For Europe, the agreement between the first two transitions is particularly consistent, whereas for the rest of the world, while the uncertainties in risk transitions overlap, the UK risk transitions are generally a bit higher. This data might reflect affluent UK and European populations, which have well established health systems and, as such, could be deemed more resilient to climate change than some of the lower-income and middle-income countries. As such, a higher temperature rise is required before increases in the hazard-relevant health burdens are predicted, which gives us confidence that our collective experts were aligned with those of the IPCC.

On average, risk transitions occur at lower global mean temperatures for heat-related health hazards than for other hazards. Transitions from an undetectable (white) to a moderate level of risk (orange for increase; green for decrease) might have already occurred for all major hazards, as indicated by the uncertainty in possible transitions (vertical transition lines) being below or encompassing the current global warming temperature anomaly of 1·2°C (figure 2). This signal can be gleaned from the detection and attribution literature, which has, for instance, indicated a detectable change in risks for health hazards globally.[33] Focusing on the UK, full attribution studies only exist for heat-health,[34,35] but they show positive detection has already occurred, in line with our assessment. For the other hazards considered in figure 2, there exists health-hazard literature from other parts of the world to help inform the transitions, or UK-specific literature that is not necessarily focused on the health part of the hazard, including the cold,[36] storms and flooding,[37,38] allergens,[39] and wildfires,[40] which we show are the least likely to have a detectable transition. Even stabilising climate at the upper Paris Agreement goal of 2°C relative to pre-industrial levels would mean that every UK hazard relevant to health might have gone through two risk transitions, with cold-health hazards being the least likely. The hazard where fewest experts answered questions was the compound hazard (figure 2), which includes allergies and infectious diseases (table). The uncertainty in the transitions is however comparable, or lower, than most other hazards except for heat or drought. This finding suggests that we had fewer experts in this topic within the SEJ process, potentially highlighting the complexity of these types of health hazards, but also that the perception between the experts was consistent.

A synthesis of UK health outcomes now and in the future

While the hazards are the start of the UK's climate-health story, the overall mortality burden is governed by how those hazards are causally linked to mortality, and by any ameliorative strategies that are implemented to mitigate these risks. From statistical modelling we know, for instance, that few people, if any, die from wildfires in the UK, but that many thousands die from extreme temperatures.[41] Here, the SEJ allows us to develop a schematic of all known weather-mortality and climate-mortality in the UK, along with the specific causes of death and how they could change in the future. Such a synthesis is highly complex (figure 3), and this is undoubtedly why it has not been created before. Present-day mortality,

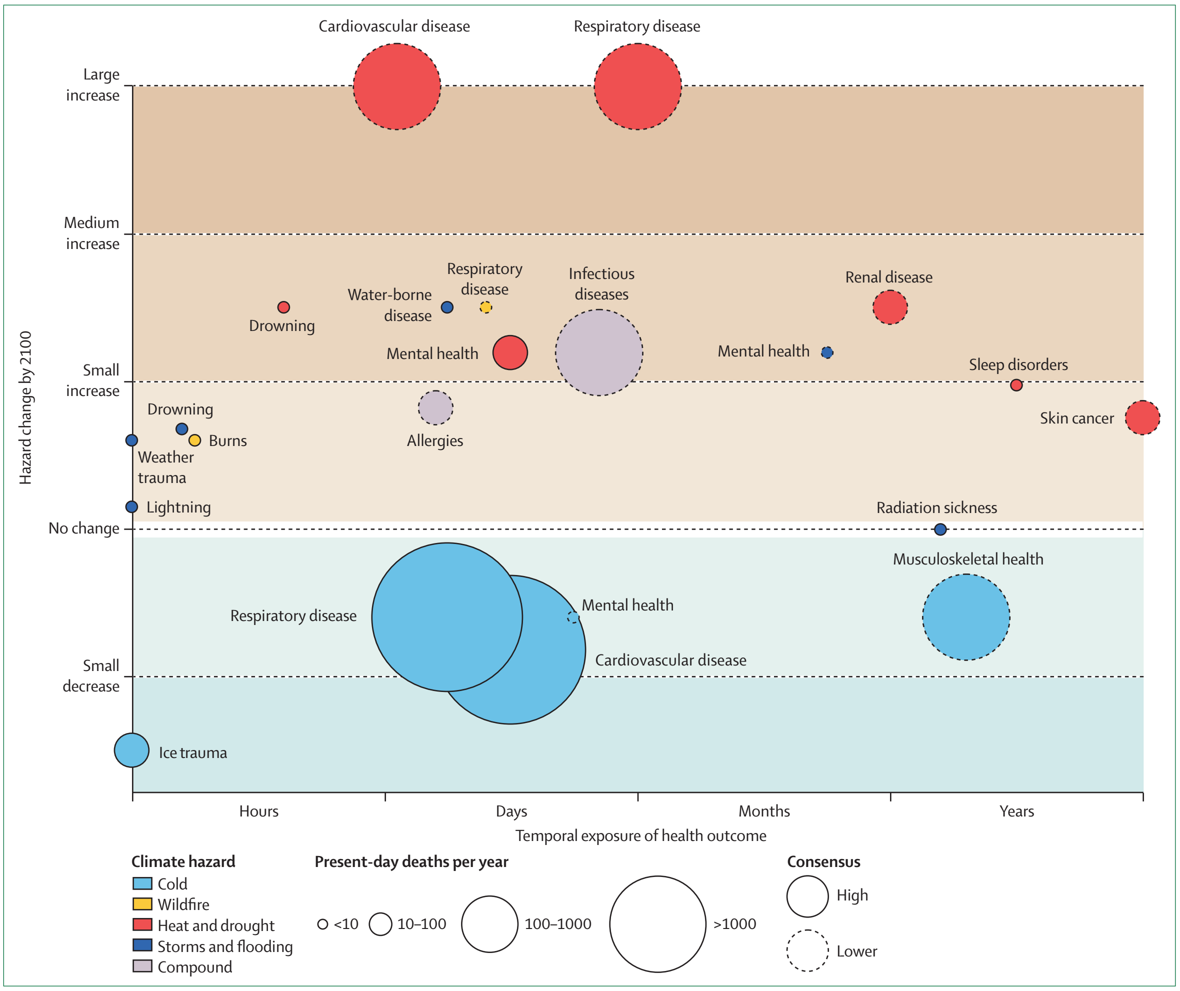

Figure 3: **Synthesis of mortality from weather hazards and climate patterns in the UK**
The circle sizes show present-day yearly human mortality estimates due to various climate hazards, categorised by the number of deaths (<10, 11–100, 101–1000, and >1000 per year). Circle colours correspond to specific climate hazards. The compound hazard category encompasses deaths from multiple weather types, such as allergenic pollen affected by wind, rain, and temperature. The x axis measures the duration of exposure to these hazards leading to mortality, while the y axis reflects expert predictions on the future changes in these hazards, based on survey calibration (appendix 2 pp 11–12). Expert consensus on future hazard changes is indicated by the ring type around each circle: solid black for high and dashed for medium or low. Further details and individual expert responses are in appendix 2 (p 1). As an example of interpretation, heat-related cardiovascular disease was mainly linked to temperature but also affected by humidity and solar radiation, and is expected to see a large increase in the future. Currently, it accounts for 100–1000 annual deaths in the UK occurring after days of exposure.

indicated by the size of the circle, is largest from heat or drought and cold hazards, although the compound climate hazard leading to infectious disease-related mortality is also large. The largest heat and drought circles indicate a mortality rate of 100–1000 deaths per year, and these are expected to amplify as they are also related to the largest future increase in hazard (figure 3, y axis). For some of the cold mortality causes, the current mortality rate is even higher (>1000 deaths per year), although the future change in the hazard is considerably smaller, albeit with large uncertainty in the expert responses (appendix 2 p 2). Current mortality outcomes in all but the smallest category are particularly dominated by a risk to older people (table), and heat-related cardiovascular and respiratory mortality is expected to see the largest future increase, which is important given the UK's ageing population.

The primary specific causes of mortality from temperature hazards are cardiovascular failure, respiratory disease, or musculoskeletal impediment, which occurs only due to cold temperatures. The cardiovascular response to extremely high and low temperatures is well documented; for example, changes in vascular constriction with temperature can lead to cardiac problems (eg, heatstroke and hypothermia), and this is represented well in the UK climate-health literature (figure 4). For respiratory disease, there is a debate in the community on the aetiology, more so for cold-related outcomes than heat-related outcomes. Some studies argue for a seasonal effect, as shown by comparing countries with different climates,[42,43] while other studies show that when seasonality is controlled for, a clear cold-mortality response is still observed.[41,44,45] The cold-related musculoskeletal mortality, brought on from reduced physical activity on cold days resulting in poorer cardiovascular health over years, is not represented in many of the temperature all-cause mortality studies as the population needs to be exposed to the cold for a long period for this effect to become clear, and most studies only consider lagged effects of weeks.[44] This result is important because even where long mortality records exist, it is unlikely that our data are complete enough to accurately model such exposures, yet anecdotal evidence, such as workshops with general practitioners and musculoskeletal consultants, suggests that they are. Such a health burden can be a substantial cost to health services, and a better understanding is important for improved health financing. Similar arguments can be made for the heat-related renal disease, and skin cancer health burdens, that indicate 10–100 deaths per year, with both requiring exposure times of years before mortality occurs (figure 3). Of note, with renal disease there are multiple relevant exposure timescales including a shorter one (days) with acute renal failure, and a longer one (months or even years) from persistent or reoccurring heat-exposure. The renal mortality burden is particularly problematic in the UK context, because the relevant heat hazard (figure 3, y axis) is the third largest increase in the future of all hazards, yet renal outcomes are considerably under-represented in the current literature (figure 4). Lastly, sleep disorders represent another potential long-exposure pathway to mortality, but the survey revealed a good degree of consensus that this health burden is somewhat low compared with other pathways, albeit based on a small literature base. Sleep disorders include the longer-term exposure effects of hot nights on neurodegenerative diseases, such as Alzheimer's disease or Parkinson's disease, but these diseases also have a shorter timescale response, such as stroke. Regarding these shorter timescales, there is evidence of a notable current and future health burden, in the UK[46] and elsewhere,[47] which is represented in our temperature-related cardiovascular disease circles (figure 3).

Compound hazard is also indicated to have a large mortality burden, with allergies causing 10–100 deaths per year, and infectious diseases causing 100–1000 deaths per year (figure 3). While both mortality rates are high, there is also a great deal of uncertainty in the experts' estimates of these (appendix 2 p 2), more so than any other health outcome. Such uncertainty could reflect the complexities of the weather and climate link with these health outcomes, both in terms of their prediction and their effect on mortality. The expert contributors might have had less experience with infectious diseases and allergens, which were grouped together in the compound hazard category in the expert survey, or might not have felt confident in providing specific answers about these broad categories. The literature for these hazards within the UK primarily focuses (more than 80% of papers) on morbidity, rather than mortality (appendix 2 p 4). The literature on the effect of climate on infectious disease also primarily relates to vector-borne disease. The main vector-borne infectious diseases relevant for the UK now is tick-borne Lyme disease, but tick-borne encephalitis is potentially becoming more relevant as the UK winters are warm,[48] and vectors for both diseases could start having longer active seasons as the climate suitability changes.[49] In the future, other

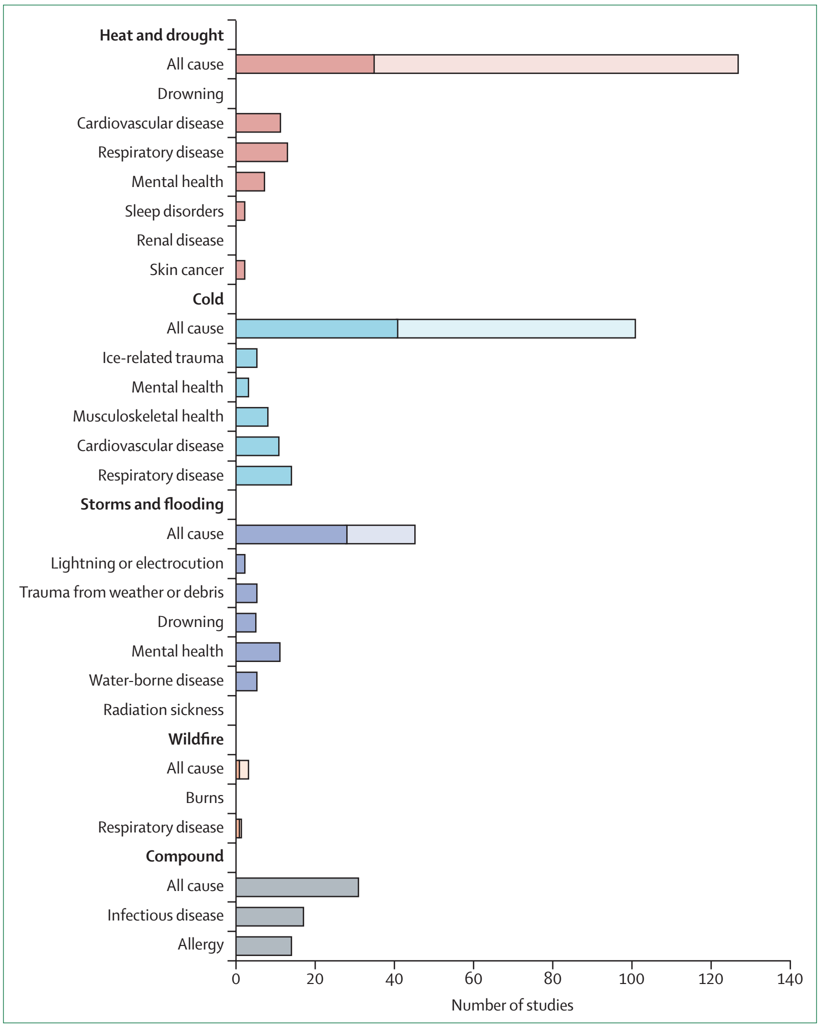

Figure 4: **The number of peer-reviewed studies on each of the health outcomes in the literature, for morbidity and mortality**

These results are based on keyword searches in the Web of Science and Scopus databases, with the geographical location of studies restricted to the UK or wider regions including the UK. Only articles that were published in or after 2003 were included. Details of the systematic review are given in the Methods section, and included articles are listed in appendix 1 (p 8). The bars are colour-coded according to the hazard leading to health outcomes, with red indicating heat, light blue indicating cold, dark blue indicating storms or flooding, orange indicating wildfire, and grey indicating compound hazard. Bars indicating "all cause" are the sum of peer-reviewed studies of all health outcomes for each weather hazard (dark), plus the number of studies on all-cause mortality for that hazard (light), so can be interpreted as the total number of studies investigating health outcomes related to each weather hazard. Articles can appear in multiple weather hazards, but are categorised as "all cause" if multiple health outcomes related to the same weather hazard are reported, to avoid multiple counting.

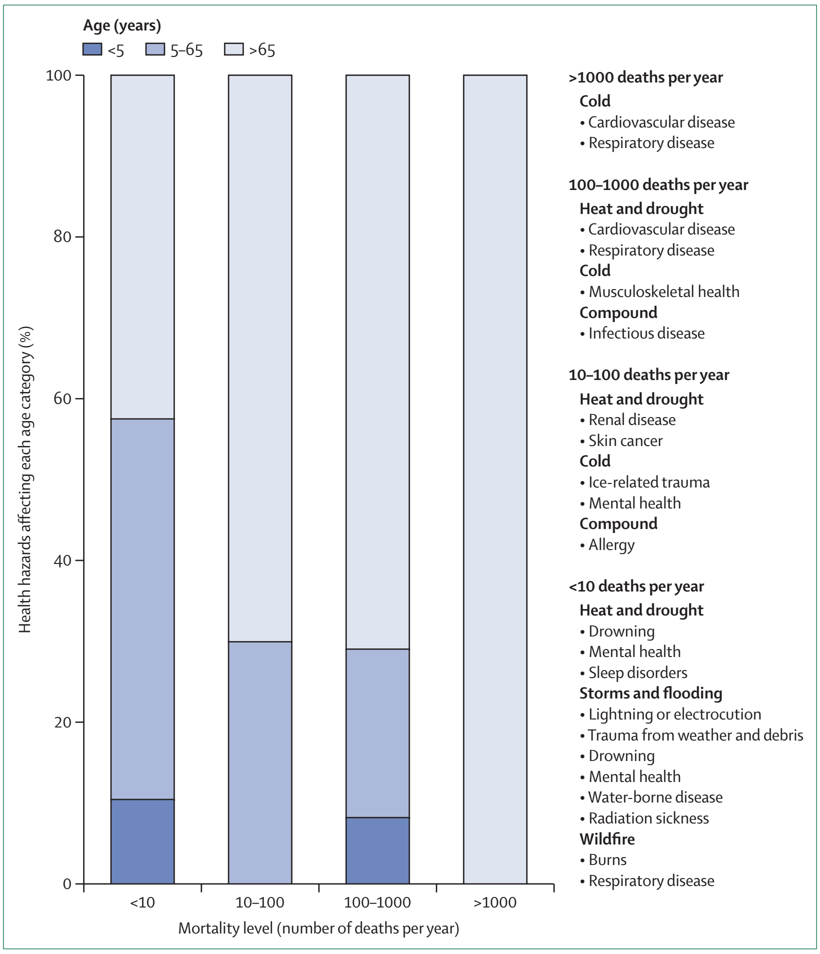

***Figure 5:* Differential mortality based on age group**
For each present-day mortality level category (less than 10 deaths per year, between 10 and 100 deaths per year, between 100 and 1000 deaths per year, or over 1000 deaths per year), the age-dependent susceptibility of all health hazards within the category is shown as a percentage. Age-dependent susceptibility for each hazard or outcome is approximated from values in the systematic literature review. To calculate the percentages for each mortality level category, one or more age group was assigned to each hazard or outcome in that category (multiple age groups were assigned when there were considerable vulnerabilities in more than one age group). The proportion of one age group is the number of hazards or outcomes with that age group assigned (assigning a value of 1 or 2 where two age groups were assigned, or 1 or 3 where three were assigned), divided by the total number of hazards or outcomes at the mortality level.

vector-borne diseases are expected to contribute to the UK health burden, notably mosquito-borne West Nile Virus and potentially dengue,[32] and the mortality rate might change considerably in the future. More detailed investigation of each class of compound hazard might be necessary to untangle the projected effects and how they differ between tick-borne, mosquito-borne, directly transmitted, or other infectious diseases and different types of allergens.

The health hazards with the seemingly lightest current and future burden on the UK are from storms and flooding and wildfires. These hazards all have present-day weather-mortality rates of less than 10 deaths per year, often with only small, estimated hazard changes in the future. Although these hazards might seem less relevant for the future of the UK, it could depend on how the extremes of the hazards relate to mortality. If this relationship is sufficiently non-linear, and we have not experienced the relevant part of the hazard–mortality relationship, it could be problematic.[12] For instance, significant increases in winter precipitation could suddenly overwhelm drainage systems, leading to a sharp rise in water-borne diseases. For many of these hazards, there was a high expert consensus on the current mortality rate, especially for lightning strikes, trauma from storm debris, exposure to radioactive material from flooding, and burning from wildfires, but there was often less agreement on their future change (appendix 2 p 2).

The health hazards currently with small rates of mortality tend to affect a wider age range of the population (figure 5). Notably, mental health outcomes associated with extreme temperature often affect those of working age (age 18–65 years),[50,51] although outcomes following exposure to flooding also affect older people.[52] The particularly rapid exposure health outcomes (eg, storms and flooding-related drowning, trauma, or lightning) can often be related to outdoor work and leisure; for example, firefighting, hiking, swimming, and commercial fishing,[53–55] primarily affecting those of working age. However, there is also considerable susceptibility in older populations from exposure to flooding and consequential drowning (figure 5).[56]

Mental health related to flooding also shows a current low health burden (figure 3) but requires closer inspection. There is a comparatively large amount of UK literature linking flooding to mental health, especially anxiety, depression, and post-traumatic stress disorder (figure 4)—eg, the 2013 and 2014 southern UK floods.[57,58] The explicit link to mortality has not been made yet, as reflected in the size of the circle, possibly because the exposure timescales are of the order of many months, or perhaps because we have not yet reached that part of the hazard–health relationship. Similar, out of sample arguments could be made with other hazards, including faster spreading future wildfires that catch communities off guard, although no current literature exists for the UK on this topic.

Discussion

The changing state of weather and climate patterns leads to some of the most crucial questions regarding the UK's health landscape. What is the burden of different weather-related and climate-related mortality causes in the UK currently? How is climate change expected to alter that burden? Are there potential long-exposure health outcomes that are not fully appreciated? What new climate-related health threats might emerge in the future? Despite the UK having some of the most reliable and complete health and climate data, we still do not have the process-based or statistical models to address these questions comprehensively, although for some hazards models are available.[44,59,60] Such questions lie at the heart of current and future UK resilience to weather and climate, from short timescales affecting emergency services during flooding events, to longer timescales such as temperature-resilient housing to cope with persistent heat. An SEJ should be used for this type of problem, which involves inadequate data, partial knowledge, and large uncertainties, allowing us to develop the schematic in figure 3. As with any analysis of this type,[13,16] we present a collective opinion of a group, rather than an immutable fact or conclusion. Various factors, such as new knowledge or the development of new climate-health models, could change the minds of a group of experts resulting in changes to their assessment of relative risk.

Synthesising the weather-mortality in the UK is the first part of a complex climate-health nexus. There are multiple dimensions that could be expanded on, including how the schematic in figure 3 would change with different levels of future adaptation or socioeconomic change, as was done for several climate risks in the IPCC Sixth Assessment Report.[32] Other relevant expansions of the schematic could be to consider different susceptible communities, or to focus on morbidity instead of mortality. Some of the cause-specific health outcomes are well studied, with the largest number of publications focused on temperature-related causes, specifically cardiovascular, respiratory, and mental health outcomes (figure 4). However, others such as heat-related renal disease and skin cancer are not well studied. Our analysis indicates a current health burden of 10–100 deaths per year for both outcomes, with future climate change expected to increase this burden. Cold-related musculoskeletal mortality is another notable gap: while there are several studies on this, they all discuss the morbidity effects rather than mortality (figures 4; appendix 2 p 4), and this uncertainty is reflected in the expert consensus on future changes (appendix 2 p 2). In general, the longer-exposure health outcomes are more understudied than the shorter-exposure ones. This could be because, by construction, longer time-series health datasets are required—for instance, datasets that follow cohorts of the population throughout their life course. Causal inference in such instances also becomes highly problematic, because these datasets are often annual snapshots of an individual's health and do not systematically follow them throughout the year.

Drawing together all health hazards in the UK, including across temporal-exposure scales, allows for an interpretation into how one might start to adapt (eg, to changing temperatures). Such an adaptation might introduce non-linearity to health outcome results, which is hard to capture in our analysis. An example that could highlight this issue is the infamous 2003 European heatwave. The heat-related death toll in France was substantial,[61] and was likely higher than it should have been due to inadequate national adverse weather plans. Indeed, heatwaves of similar magnitudes in later years led to substantially lower heat-related mortality.[6,62] As such, had our expert judgement been undertaken a few years before that heatwave, it might have yielded different responses to if it had been completed a few years after. The way in which populations adapt varies widely depending on the hazard and the current level of perceived risk. For instance, there are important differences in the current mortality toll, climate change signal, and exposure of heat-related outcomes versus cold-related outcomes (figure 3). Understanding differential vulnerability to climate change in the context of health will allow local councils and the health services to prioritise investments to build resilience and reduce health inequalities. Some expert judgements of the vulnerability to environmental hazards already exist in other countries,[20–22] but linking these types of analyses to the physiological hazard–health pathways in our study is non-trivial, at least in the context of an expert judgement. Such a linkage would allow us to start generating adaptation pathways. To synthesise readily available interventions and to consider how behaviour changes and infrastructure design will continue to make a difference to health and wellbeing, which will be fundamental to understand the altered risks from future climate change.

While the UK is a logical place to start such a health synthesis, because of the evidence base and data already available, the distribution of weather-related and climate-related mortality causes will be very different for various countries around the world. Crucially, in many lower-income and middle-income countries, investment in town and population resilience is primarily driven by the evidence of improvements in health. With a systematic weather-health and climate-health synthesis, as done here but gradually including more and more countries, we could start to build a more complete picture of the current and future global health burden from weather and climate change. The current estimates are crucially out of date,[63] and probably inaccurate by a large margin.[64] We need to start converging on more accurate and justifiable numbers, using all the tools available to us. Here, we have presented a novel way to do this.

Contributors
DM conceived the experiment. JLG managed the survey process. DM, YTEL, EB, and JLG performed the analysis and made the figures. EB did the systematic literature review. DM, YTEL, RB, LBF, KLE, BG, GJG, and CHS co-designed the expert survey. All co-authors contributed to the study design and commented on manuscript drafts.

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References

1 Ebi KL, Capon A, Berry P, et al. Hot weather and heat extremes: health risks. *Lancet* 2021; **398:** 698–708.

2 Sherwood SC, Huber M. An adaptability limit to climate change due to heat stress. *Proc Natl Acad Sci USA* 2010; **107:** 9552–55.

3 Eunice Lo YT, Mitchell DM, Buzan JR, et al. Optimal heat stress metric for modelling heat-related mortality varies from country to country. *Int J Climatol* 2023; **43:** 5553–68.

4 Rifkin DI, Long MW, Perry MJ. Climate change and sleep: a systematic review of the literature and conceptual framework. *Sleep Med Rev* 2018; **42:** 3–9.

5 Watts N, Adger WN, Agnolucci P, et al. Health and climate change: policy responses to protect public health. *Lancet* 2015; **386:** 1861–914.

6 Mitchell D, Kornhuber K, Huntingford C, Uhe P. The day the 2003 European heatwave record was broken. *Lancet Planet Health* 2019; **3:** e290–92.

7 Fischer E, Sippel S, Knutti R. Increasing probability of record-shattering climate extremes. *Nat Clim Chang* 2021; **11:** 689–95.

8 Thompson V, Kennedy-Asser AT, Vosper E, et al. The 2021 western North America heat wave among the most extreme events ever recorded globally. *Sci Adv* 2022; **8:** eabm6860.

9 van Daalen KR, Romanello M, Rocklöv J, et al. The 2022 Europe report of the *Lancet* Countdown on health and climate change: towards a climate resilient future. *Lancet Public Health* 2022; **7:** e942–65.

10 UK Climate Risk. Chapter 5. Health, communities and the built environment. 2021. https://www.ukclimaterisk.org/wp-content/uploads/2021/06/CCRA3-Chapter-5-FINAL.pdf (accessed Aug 14, 2024).

11 UK Health Security Agency. Chapter 2. Temperature effects on mortality in a changing climate. 2023. https://assets.publishing.service.gov.uk/media/659ff712e96df5000df844bf/HECC-report-2023-chapter-2-temperature.pdf (accessed Aug 14, 2024).

12 Mitchell D. Climate attribution of heat mortality. *Nat Clim Chang* 2021; **11:** 467–68.

13 Oppenheimer M, Little CM, Cooke RM. Expert judgement and uncertainty quantification for climate change. *Nat Clim Chang* 2016; **6:** 445–51.

14 Collins M, Knutti R. Long-term climate change: projections, commitments and irreversibility. 2013. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter12_FINAL.pdf (accessed Aug 14, 2024).

15 Bamber JL, Aspinall W. An expert judgement assessment of future sea level rise from the ice sheets. *Nat Clim Chang* 2013; **3:** 424–27.

16 Bamber JL, Oppenheimer M, Kopp RE, Aspinall WP, Cooke RM. Ice sheet contributions to future sea-level rise from structured expert judgment. *Proc Natl Acad Sci USA* 2019; **116:** 11195–200.

17 Bamber J, Oppenheimer M, Kopp R, Aspinall W, Cooke RM. Ice sheet and climate processes driving the uncertainty in projections of future sea level rise: findings from a structured expert judgement approach. *Earths Future* 2022; **10:** e2022EF002772.

18 Ebi KL, Boyer C, Ogden N, et al. Burning embers: synthesis of the health risks of climate change. *Environ Res Lett* 2021; **16:** 044042.

19 Rennert K, Errickson F, Prest BC, et al. Comprehensive evidence implies a higher social cost of CO_2. *Nature* 2022; **610:** 687–92.

20 Martín Y, Rodrigues Mimbrero M, Zúñiga-Antón M. Community vulnerability to hazards: introducing local expert knowledge into the equation. *Nat Hazards* 2017; **89:** 367–86.

21 Räsänen A, Heikkinen K, Piila N, Juhola S. Zoning and weighting in urban heat island vulnerability and risk mapping in helsinki, finland. *Reg Environ Change* 2019; **19:** 1481–93.

22 Shih W-Y, Mabon L. Understanding heat vulnerability in the subtropics: insights from expert judgements. *Int J Disaster Risk Reduct* 2021; **63:** 102463.

23 Lo YTE, Mitchell DM, Thompson R, O'Connell E, Gasparrini A. Estimating heat-related mortality in near real time for national heatwave plans. *Environ Res Lett* 2022; **17:** 24017.

24 UK Government. 2023 national risk register. 2023. https://www.gov.uk/government/publications/national-risk-register-2023 (accessed May 5, 2024).

25 Gaupp F, Hall J, Mitchell D, Dadson S. Increasing risks of multiple breadbasket failure under 1.5 and 2 c global warming. *Agric Syst* 2019; **175:** 34–45.

26 Koubi V. Climate change and conflict. *Annu Rev Polit Sci* 2019; **22:** 343–60.

27 Cooke RM, Marti D, Mazzuchi T. Expert forecasting with and without uncertainty quantification and weighting: what do the data say? *Int J Forecast* 2021; **37:** 378–87.

28 Aspinall WP, Cooke RM. Quantifying scientific uncertainty from expert judgement elicitation. In: Rougier J, Sparks S, Hill LJ, eds. Risk and uncertainty assessment for natural hazards. Cambridge: Cambridge University Press, 2013: 64–99.

29 Cooke RM. The aggregation of expert judgment: do good things come to those who weight? *Risk Anal* 2015; **35:** 12–15.

30 Page MJ, Moher D, Bossuyt PM, et al. PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews. *BMJ* 2021; **372:** n160.

31 Pörtner H-O, Roberts DC, Adams H, et al. Summary for policymakers. 2022. https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_SummaryForPolicymakers.pdf (accessed Aug 14, 2024).

32 Bednar-Friedl B, Biesbroek R, Schmidt DN, et al. Europe (chapter 13). In: Pörtner H-O, Roberts DC, Tignor M, et al, eds. IPCC 2022: climate change 2022: impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK, and New York, NY, USA: Cambridge University Press, 2022: 1817–927.

33 Newman R, Noy I. The global costs of extreme weather that are attributable to climate change. *Nat Commun* 2023. **14:** 6103.

34 Mitchell D, Heaviside C, Vardoulakis S, et al. Attributing human mortality during extreme heat waves to anthropogenic climate change. *Environ Res Lett* 2016; **11:** 074006.

35 Perkins-Kirkpatrick SE, Stone DA, Mitchell DM, et al. On the attribution of the impacts of extreme weather events to anthropogenic climate change. *Environ Res Lett* 2022; **17:** 024009.

36 Christidis N, Stott PA, Ciavarella A. The effect of anthropogenic climate change on the cold spring of 2013 in the United Kingdom. *Bull Am Meteorol Soc* 2014; **95:** S79–82.

37 Kay AL, Booth N, Lamb R, Raven E, Schaller N, Sparrow S. Flood event attribution and damage estimation using national-scale grid-based modelling: winter 2013/2014 in Great Britain. *Int J Climatol* 2018; **38:** 5205–19.

38 Frame DJ, Wehner MF, Noy I, Rosier SM. The economic costs of hurricane Harvey attributable to climate change. *Clim Change* 2020; **160:** 271–81.

39 Anderegg WRL, Abatzoglou JT, Anderegg LDL, Bielory L, Kinney PL, Ziska L. Anthropogenic climate change is worsening North American pollen seasons. *Proc Natl Acad Sci USA* 2021; **118:** e2013284118.

40 Lewis SC, Blake SAP, Trewin B, et al. Deconstructing factors contributing to the 2018 fire weather in Queensland, Australia. *Bull Am Meteorol Soc* 2020; **101:** S115–22.

41 Gasparrini A, Masselot P, Scortichini M, et al. Small-area assessment of temperature-related mortality risks in England and Wales: a case time series analysis. *Lancet Planet Health* 2022; **6:** e557–64.

42 Ebi KL, Mills D. Winter mortality in a warming climate: a reassessment. *WIREs Clim Chang* 2013; **4:** 203–12.

43 Kinney PL, Schwartz J, Pascal M, et al. Winter season mortality: will climate warming bring benefits? *Environ Res Lett* 2015; **10:** 064016.

44 Gasparrini A, Guo Y, Hashizume M, et al. Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *Lancet* 2015; **386:** 369–75.

45 Arbuthnott K, Hajat S, Heaviside C, Vardoulakis S. What is cold-related mortality? A multi-disciplinary perspective to inform climate change impact assessments. *Environ Int* 2018; **121:** 119–29.

46 Gong J, Part C, Hajat S. Current and future burdens of heat-related dementia hospital admissions in England. *Environ Int* 2022; **159:** 107027.

47 Yin P, Gao Y, Chen R, et al. Temperature-related death burden of various neurodegenerative diseases under climate warming: a nationwide modelling study. *Nat Commun* 2023; **14:** 8236.

48 Voyiatzaki C, Papailia SI, Venetikou MS, Pouris J, Tsoumani ME, Papageorgiou EG. Climate changes exacerbate the spread of *Ixodes ricinus* and the occurrence of lyme borreliosis and tick-borne encephalitis in Europe—how climate models are used as a risk assessment approach for tick-borne diseases. *Int J Environ Res Public Health* 2022; **19:** 6516.

49 UK Health Security Agency. Chapter 8. Direct and indirect effects of climate change on vectors and vector-borne diseases in the UK. Jan 15, 2024. https://assets.publishing.service.gov.uk/media/65708af2809bc3001330819c/HECC-report-2023-chapter-8-vector-borne-diseases.pdf (accessed Aug 14, 2024).

50 Page LA, Hajat S, Kovats RS, Howard LM. Temperature-related deaths in people with psychosis, dementia and substance misuse. *Br J Psychiatry* 2012; **200:** 485–90.

51 Kim Y, Kim H, Gasparrini A, et al. Suicide and ambient temperature: a multi-country multi-city study. *Environ Health Perspect* 2019; **127:** 117007.

52 Walker-Springett K, Butler C, Adger WN. Wellbeing in the aftermath of floods. *Health Place* 2017; **43:** 66–74.

53 Elsom DM. Factors contributing to a long-term decrease in national lightning fatality rates: case study of the United Kingdom with wider implications. *Int J Disaster Risk Reduct* 2018; **31:** 341–53.

54 Elsom DM, Webb JDC. Deaths and injuries from lightning in the UK, 1988–2012. *Weather* 2014; **69:** 221–26.

55 Roberts SE. Fatal work-related accidents in UK merchant shipping from 1919 to 2005. *Occup Med* 2008; **58:** 129–37.

56 Di Mauro M, De Bruijn K. Application and validation of mortality functions to assess the consequences of flooding to people. *J Flood Risk Manag* 2012; **5:** 92–110.

57 Munro A, Kovats RS, Rubin GJ, et al. Effect of evacuation and displacement on the association between flooding and mental health outcomes: a cross-sectional analysis of UK survey data. *Lancet Planet Health* 2017; **1:** e134–41.

58 Waite TD, Chaintarli K, Beck CR, et al. The English national cohort study of flooding and health: cross-sectional analysis of mental health outcomes at year one. *BMC Public Health* 2017; **17:** 129.

59 Vicedo-Cabrera AM, Guo Y, Sera F, et al. Temperature-related mortality impacts under and beyond Paris Agreement climate change scenarios. *Clim Change* 2018; **150:** 391–402.

60 Vicedo-Cabrera AM, Scovronick N, Sera F, et al. The burden of heat-related mortality attributable to recent human-induced climate change. *Nat Clim Chang* 2021; **11:** 492–500.

61 Pirard P, Vandentorren S, Pascal M, et al. Summary of the mortality impact assessment of the 2003 heat wave in France. *Euro Surveill* 2005; **10:** 153–56.

62 Fouillet A, Rey G, Wagner V, et al. Has the impact of heat waves on mortality changed in France since the European heat wave of summer 2003? A study of the 2006 heat wave. *Int J Epidemiol* 2008; **37:** 309–17.

63 WHO. Comparative quantification of health risks: global and regional burden of disease attribution to selected major risk factors. Oct 18, 2004. https://www.who.int/publications/i/item/9241580313 (accessed Aug 14, 2024).

64 Carlson CJ, Alam MS, North MA, Onyango E, Stewart-Ibarra AM. The health burden of climate change: a call for global scientific action. *PLoS Clim* 2023; **2:** e0000126.

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