Health risks of warming of 1.5 °C, 2 °C, and higher, above pre-industrial temperatures

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Background: In response to the Paris Agreement under the United Nations Framework Convention on Climate Change, the research community was asked to estimate differences in sectoral-specific risks at 1.5 °C and 2 °C increases in global mean surface air temperature (SAT) above pre-industrial temperatures. Projections of the health risks of climate change typically focus on time periods and not on the magnitude of temperature change.

Objective: Summarize projections of health risks associated with temperature extremes and occupational heat stress, air quality, undernutrition, and vector-borne diseases to estimate how these risks would differ at increases in warming of 1.5 °C, 2 °C, and higher.

Methods: A comprehensive search strategy included English language publications since 2008 projecting health risks of climate change identified through established databases. Of 109 relevant publications, nearly all were for future time periods (e.g. in 2030 and 2050) rather than future SAT thresholds. Time periods were therefore converted to temperature changes based on the models and scenarios used.

Results: Warming of 1.5 °C is reached in about the 2030s for all multi-model means under all scenarios and warming of 2 °C is reached in about the 2050s under most scenarios. Of the 40 studies projecting risks at 1.5 and 2 °C increases of SAT, risks were higher at 2 °C for adverse health consequences associated with exposures to high ambient temperatures, ground-level ozone, and undernutrition, with regional variations. Risks for vector-borne diseases could increase or decrease with higher global mean temperatures, depending on regional climate responses and disease ecology.

Conclusions: The burden of many climate-sensitive health risks are projected to be greater at an increase of 2 °C SAT above pre-industrial temperatures than at 1.5 °C. Future projection studies should report results based on changes in global and regional mean SATs and time, to facilitate quantitative analyses of health risks and to inform the level of ambition and timing of adaptation interventions.

Introduction

Climate change is increasing global and regional temperatures and precipitation in some regions, the frequency and intensity of extreme weather and climate events, and sea levels and ocean acidification (IPCC 2013). Exposure to these changes have adverse consequences for human health and well-being (Cramer et al 2014, Ebi et al 2017, Smith et al 2014). Smith et al (2014) concluded that if climate change continues as projected under higher emission scenarios, major changes in ill health would include:
• Greater risks of injuries, diseases, and death due to more intense heatwaves and fires (very high confidence);
• Increased risk of undernutrition resulting from diminished food production and water supply in poor regions (high confidence);
• Consequences for health from lost work capacity and reduced labor productivity (high confidence);
• Increased risks of food- and waterborne diseases (very high confidence) and vector-borne diseases (medium confidence);
• Modest reductions in cold-related morbidity and mortality in some areas due to fewer cold extremes (low confidence), geographic shifts in food production, and reduced capacity of disease-carrying vectors due to exceedance of thermal thresholds (medium confidence). These positive effects will be increasingly outweighed, worldwide, by the magnitude and severity of the negative effects of climate change (high confidence).

Few projections supporting these summary statements quantified how risks could differ at specific increases in global mean surface air temperature (SAT). To determine the extent of additional health risks of climate change at increases in global mean SAT of 1.5°C, 2°C, and higher, we reviewed recent projections of health risks associated with temperature extremes, heat stress as it affects occupational health, air quality, undernutrition, and vector-borne diseases. This information can be used to inform implementation of the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC 2015).

Methods

The search strategy included projections of identified climate-sensitive health outcomes over this century published in or since 2008 through November 2017. We chose 2008 to include projections of health risks assessed in Smith et al (2014). We conducted a comprehensive literature search of the peer-reviewed, global literature, with iterative searches of PubMed, Web of Science, Ovid MEDLINE, and Embase to identify English publications using specific health outcomes and climate or climate change as search terms; search terms were applied to publication titles and abstracts (Annex 1 in supplemental material available at stacks.iop.org/ERL/13/063007/mmedia). Publications were identified for temperature extremes, occupational health, ground-level ozone and particulate matter, undernutrition, and vector-borne diseases such as malaria, dengue, West Nile virus, Lyme and other tick-borne diseases, as well as Chagas disease and leishmaniasis. We did not include food- and water-borne diseases because of the paucity of literature.

The initial database search returned 2649 publications. After removing duplicates and publications whose title or abstract indicated the analyses did not include projections of the risks of climate-sensitive health outcomes (e.g. morbidity or mortality and potential health impacts of temperature extremes) under a changing climate, 1891 publications remained. The reference lists of all publications including projections of health risks were searched for additional possible citations. The literature search was updated during peer review to identify and include additional submissions.

Abstracts were reviewed to identify papers that quantified climate change projections of health risks, leaving 109 studies. These publications were critically reviewed and summarized in terms of the region of interest; the health outcome metric used; baseline health information; climate model(s) and scenario(s) used; the time periods of interest; impacts at the baseline reported in the study; projected risks at 1.5°C, 2°C, and higher degrees of warming; and other factors considered, such as population change. Information on warming above 2°C was included to put the risks of the lower thresholds of warming into perspective. Supplemental materials includes summary tables organized by health outcome, with two tables for each health outcome. One table summarizes publications projecting risks for that health outcome at 1.5°C and 2°C increase in SAT (e.g. the study projected for both degrees of temperature change) and another table that summarizes other publications projecting health risks for that health outcome. The first table for each health outcome directly addresses the request from the UNFCCC to understand the risks of warming of 1.5°C and 2°C, while the second summarizes other projections, to provide further quantifications of the health risks of climate change. There is limited information on the health risks of warming of more than 2°C in the supplementary tables; these projections are not covered in depth because of greater uncertainties regarding health outcomes associated with higher degrees of warming and also because of inconsistencies in the time periods projected.

The diversity of baselines, scenarios, climate models, and health models used in the projections precludes quantitative comparisons of the studies. Qualitative comparisons of the results were made using expert judgement.

Nearly all projections of the health risks of climate change were for future time periods (e.g. risks in 2030 and 2050), not for specific thresholds of global mean SAT changes. Analysis therefore required a conversion from time to temperature. The year for which global mean SAT is projected to reach 1.5°C and 2°C above preindustrial levels was estimated using global climate model (GCM) projections employed within each health study. For each study, the following were characterized: (1) the model generation (Coupled Model Intercomparison Project (CMIP) 3 or CMIP5);
(2) the emissions scenario(s) (SRES A1B/A2/B1 for CMIP3, or Representative Concentration Pathway (RCP) 2.6/4.5/6.0/8.5 for CMIP5); and (3) the number of GCMs used. If only one GCM was used in a study, the temperature projection(s) was used from that GCM, model generation, and emissions scenario(s). If more than one GCM was used, the multi-model mean temperature projection for that particular model generation and emissions scenario(s) was used. CMIP3 global mean SAT projections were obtained from the IPCC Data Distribution Centre (IPCC 2007). CMIP5 projections were obtained from the Royal Netherlands Meteorological Institute Climate Explorer (KNMI 2013).

Next, a baseline period was defined to estimate 1.5 °C and 2 °C global mean SAT increases. Rather than define a specific pre-industrial baseline period (which is challenging due to the different historical starting points among GCMs), within each GCM projection, the decade 2010–2019 was defined as the baseline. The rationale for this decision was that the center year of this decade—2015—is considered the first year for which observed global mean SAT reached 1.0 °C above pre-industrial conditions as defined by the 1850–1900 average (UK Met Office 2015). To determine when 1.5 °C, 2 °C, and higher degrees of warming above preindustrial conditions were reached for a given temperature projection, we created a 10 year projection window, that was then moved forward one year at a time, starting with 2011–2020, until the projected global mean SAT in the window was 0.5 °C, 1.0 °C, and higher above the 2010–2019 baseline. For perspective, we estimated, using the same approach, the magnitude by which global mean SAT is projected to exceed pre-industrial levels by the last decades of the 21st century, 2080–2089 and 2090–2099. We did not attempt to scale individual projections to 1.5 and 2 °C because doing so would introduce large uncertainties.

Results

Table 1 shows the decades when 1.5 °C, 2 °C, and higher degrees of warming are reached for multi-model means under the SRES and RCP scenarios used in the projections summarized. Warming of 1.5 °C was projected to be reached in about the 2030s for all multi-model means under all scenarios. Warming of 2 °C was projected to be reached in about the 2050s under most scenarios. Note that RCP2.6 does not reach 2 °C by the end of the century.

| Generation | Scenario | Decade 1.5 °C reached | Decade 2 °C reached | dT 2080–2099 | dT 2090–2099 |
|------------|----------|-----------------------|---------------------|-------------|-------------|
| SRES       | B1       | 2039–2048             | 2065–2074           | 2.18        | 2.27        |
| SRES       | A1b      | 2029–2038             | 2045–2054           | 3.00        | 3.21        |
| SRES       | A2       | 2032–2041             | 2048–2057           | 3.39        | 3.83        |
| RCP        | 2.6      | 2007–2016             |                     | 1.48        | 1.49        |
| RCP        | 4.5      | 2031–2040             | 2055–2064           | 2.32        | 2.37        |
| RCP        | 6.0      | 2036–2045             | 2058–2067           | 2.63        | 2.86        |
| RCP        | 8.5      | 2026–2035             | 2040–2049           | 3.90        | 4.39        |

* 2 °C not reached

Temperature-related morbidity or mortality: Of the thirty-four studies that projected increased exposure to extreme temperatures or temperature-related morbidity or mortality over this century (see supplemental material tables S1 and S2), 15 studies projected morbidity or mortality at various degrees of warming, but did not specifically compare 1.5 and 2 °C (Anderson et al 2016, Aström et al 2013, Benmarhnia et al 2014, Dong et al 2015, Gasparrini et al 2017, Kingsley et al 2016, Marsha et al 2016, Martinez et al 2016, Oleson et al 2015, Petkova et al 2017, Vicedo-Cabrera et al 2017, Voorhees et al 2011, Wang et al 2016, Weinberger et al 2017, Wu et al 2014).

Nineteen studies projected mortality at both 1.5 °C and 2 °C (Arnell et al 2018, Chung et al 2017, Doyon et al 2008, Garland et al 2015, Guo et al 2016, Hanna et al 2011, Hajat et al 2014, Honda et al 2014, Huang et al 2012, Huynen and Martens 2015, Jackson et al 2010, Kendrovski et al 2017, Li et al 2015, Li et al 2016, Petkova et al 2013, Schwartz et al 2015, Vardoulakis et al 2014, Wang et al 2015, WHO 2014), concluding that the projected magnitude of heat-related mortality at 2 °C was greater than for 1.5 °C. While higher risks were associated with greater degrees of projected warming, the magnitude of risks at different degrees of warming varied by region, presumably because of differences in average temperatures (e.g. risks are higher in regions with cooler average temperatures), population acclimatization, population vulnerability, the built environment, access to air conditioning and other factors.

In some regions (e.g. the UK under projected warming of 2 °C), cold-related mortality was projected to decrease with warmer temperatures; greater reductions in mortality were generally observed with higher degrees of warming (see SM tables S1 and S2). However, increases in heat-related mortality were projected to outweigh any reductions, with the heat-related risks increasing with greater degrees of warming (Hajat et al 2014, Huang et al 2012, Huynen and Martens 2015, Gasparrini et al 2017, Schwartz et al 2015, Vardoulakis et al 2014, Oleson et al 2015, Weinberger et al 2017).

Evidence suggests adaptation has reduced the impacts of heatwaves. Recent observations showed smaller health burdens in many countries during such events than during earlier time periods characterized...
by less adaptation (Arbuthnott et al 2016, Aström et al 2013, Chung et al 2017, Sheridan and Dixon 2016). Assumptions of additional adaptation reduced the projected magnitude of temperature-related mortality under different warming scenarios (Anderson et al 2016, Huynen and Martens 2015, Li et al 2016, Petkova et al 2017, WHO 2014).

**Impacts of heat stress on occupational health:** Four projections supported the conclusion of Smith et al (2014) that increasing heat stress associated with additional climate change could further compromise safe work activity and worker productivity during the hottest months of the year (Kjellstrom et al 2013, Kjellstrom et al 2017, Sheffield et al 2013, Dunne et al 2013). However, these projections did not compare risks at 1.5 °C and 2 °C.

Without considering the complex drivers of heat stress or the potential for acclimatization and adaptation, three studies projected that large areas of the world may become inhospitable for human health and well-being as temperatures continue to increase (Pal and Eltahir 2015, Matthews et al 2017, Sherwood and Huber 2010).

Studies projected other measures of occupational health risks from higher temperatures. Worldwide projections of the costs of preventing workplace heat-related illnesses through worker breaks suggested that total Gross Domestic Product (GDP) losses in 2100 could range from 2.6%–4.0% under high greenhouse gas emission scenarios compared to current climate conditions (Takakura et al 2017). Because the relationship between the costs of heat-related illness prevention and temperature is approximately linear, the difference in economic losses was projected to be ~0.3% less for 1.5 °C compared to 2 °C in 2100 in terms of global GDP. In China, taking into account population growth and employment structure, high temperature subsidies for employees working on extremely hot days were projected to increase from about 39 billion yuan year⁻¹ in 1979–2005 to 250 billion yuan year⁻¹ in the 2030s and 1000 billion yuan year⁻¹ in 2100 (Zhao et al 2016), with higher costs under RCP8.5 than under RCPs 4.5 and 2.6.

**Air quality:** Climate change could alter the dispersion of primary air pollutants, particularly particulate matter, and intensify the formation of secondary pollutants, such as ground-level ozone, whose formation is temperature dependent (Orru et al 2017). There is high uncertainty of projected changes in the atmospheric concentrations of ground-level ozone and particulate matter, with large regional variations in projected changes. Of the 18 studies that projected the health risks of changes in air quality (see SM tables S3 and S4), 12 projected morbidity or mortality at various degrees of warming, but did not specifically compare 1.5 °C and 2 °C (Alexeeff et al 2016, Chang et al 2014, Fang et al 2013, Fann et al 2015, García-Menéndez et al 2015, Geels et al 2015, Goto et al 2016, Liu et al 2016, Orru et al 2013, Physick et al 2014, Sun et al 2015, Wilson et al 2017).

The six studies projecting risks at both 1.5 °C and 2 °C (Dionisio et al 2017, Heal et al 2013, Lee et al 2017, Likhvar et al 2015, Silva et al 2016, Tainio et al 2013) concluded that ozone-related mortality will increase with additional warming, with the risks higher at 2 °C (Dionisio et al 2017, Heal et al 2013, Lee et al 2017, Likhvar et al 2015, Silva et al 2016, Tainio et al 2013). Reductions in precursor emissions would reduce future ozone concentrations and associated mortality. Because of uncertainties in future precursor emissions that lead to the formation of ozone, most studies held emissions constant, focusing instead on projecting the risks associated with climate change impacts.

Changes in projected particulate matter-related mortality could increase or decrease, depending on climate projections (Fang et al 2013, García-Mendez et al 2015, Geels et al 2015, Goto et al 2016, Likhvar et al 2015, Liu et al 2016, Silva et al 2017, Sun et al 2015, Tainio et al 2013). Emission assumptions also influence projected changes in particulate matter, affecting the magnitude and pattern of future mortality.

**Undernutrition:** Four studies of the risks of undernutrition with climate change supported the conclusions of Smith et al (2014) that climate change will negatively affect childhood undernutrition and stunting, through reduced food availability, and will negatively affect undernutrition-related childhood mortality and increase disability-adjusted life years lost, with the largest risks in Asia and Africa (see SM tables S5 and S6). Three studies compared health risks associated with food insecurity at 1.5 °C and 2 °C, concluding that risks are higher at 2 °C (Hasegawa et al 2016, Ishida et al 2014, WHO 2014). Warming of 1.5 °C is associated with an increase in the global undernourished population to 530–550 million; and to 540–590 million at 2 °C (Hasegawa et al 2016). Climate change impacts on dietary and weight-related risk factors were projected to increase mortality due to global reductions in food availability, fruit and vegetable consumption, and red meat consumption (Springmann et al 2016). Further, temperature increases are reducing the protein and micronutrient content of major cereal crops, which is expected to further affect food security (Myers et al 2017).

**Vector-borne diseases**

**Malaria:** Ten projections of the potential impacts of climate change on malaria globally and for China, Asia, Africa, and South America (see SM tables S7 and S8) (Caminade et al 2014, Khromi and Kumar 2016, Kwak et al 2014, Laporta et al 2015, Ren et al 2016, Semakula et al 2017, Song et al 2016, Tompkins and Caporaso 2016, Yamana et al 2016), confirmed the conclusions of Smith et al (2014) that weather and climate were among the drivers of the geographic range, intensity of transmission, and seasonality of malaria, and that
the influences of temperature and precipitation are nonlinear. Within the context of an observed 62% decline in malaria mortality since the year 2000 (WHO 2016), the three studies projecting risks at 1.5 and 2°C generally concluded the burden of malaria could increase with climate change because of a greater geographic range of the Anopheles vector and/or a longer season of disease transmission (Ren et al. 2016, Semakula et al. 2017, Song et al. 2016). Relationships between temperature and disease incidence are not necessarily linear, resulting in complex patterns of changes in risk with additional warming. Some regions are projected to become too hot and/or dry for the Anopheles mosquito, such as in northern China and parts of south and southeast Asia (Khormi and Kumar 2016, Semakula et al. 2017, Tompkins and Caporaso 2016, Yamana et al. 2016). Vector populations are projected to shift in some regions with climate change, with expansions and reductions depending on the degree of local warming, the ecology of the vector, and other factors (Ren et al. 2016).

**Aedes and dengue:** The Aedes spp. mosquito is the vector for dengue, chikungunya, yellow fever, and Zika viruses. Recent projections focused on the geographic distribution of *Aedes aegypti* and *Ae. albopictus* (principal vectors for these diseases) or on the prevalence of dengue fever, generally concluding the abundance of mosquitoes will increase by the 2030s and beyond compared to present, as will their geographic range, and of mosquitoes will increase by the 2030s and beyond (Ren et al. 2016, Bouzid et al. 2014, Butterworth et al. 2017, Campbell et al. 2015, Colon-Gonzalez et al. 2013, Fischer et al. 2011, Fischer et al. 2013, Jia et al. 2017, Khornm and Kumar 2014, Liu-Helmerson et al. 2016, Mweya et al. 2016, Ogden et al. 2014a, Proestos et al. 2015, Ryan et al. 2017, Tagaris et al. 2017, Teurlai et al. 2015, Tjaden et al. 2017, Williams et al. 2014, Williams et al. 2016) Projections at global and regional levels include North America, Southern Europe, Australia, China, Asia, New Caledonia, and Tanzania. As noted for Anopheles mosquitoes, some regions may become too hot and/or dry for Aedes spp. (Khornm and Kumar 2014). Six studies projected that, all else equal, exposure to Aedes mosquitoes and Aedes-transmitted viruses is projected to increase with greater warming (i.e. 2.0°C vs. 1.5°C) (Bouzid et al. 2014, Colon-Gonzalez et al. 2013, Fischer et al. 2011, Fischer et al. 2013, Ogden et al. 2014a, Mweya et al. 2016). Climate change is projected to expand the geographic range of chikungunya, with greater expansion with higher degrees of warming (Tjaden et al. 2017).

**West Nile virus:** Projections for North America and Europe under climate change suggested a latitudinal and altitudinal expansion of regions climatically suitable for West Nile virus transmission, particularly along the current edges of its transmission. They also suggested extension of the transmission season and an increase in the number of human cases, with the magnitude and pattern of changes varying by location and degree of warming (see tables S7 and S8 Belova et al. 2017, Brown et al. 2015, Chen et al. 2013, Harrigan et al. 2014, Morin and Comrie 2013, Semenza et al. 2016). One study projected greater risks at 2.0°C than 1.5°C (Semenza et al. 2016).

**Lyme disease and other tick-borne diseases:** Most projections concluded that climate change may expand the geographic range or shift the seasonality of Lyme and other tick-borne diseases in parts of North America and Europe (see SM tables S7 and S8) (Dhingra et al. 2013, Feria-Arroyo et al. 2014, Levi et al. 2015, Monaghan et al. 2015, Ogden et al. 2014b, Porretta et al. 2013, Simon et al. 2014, Williams et al. 2015). Two studies projected risks at 1.5°C and 2°C (Levi et al. 2015, Ogden et al. 2014b). If increased temperatures result in greater abundance of ticks and increased contact rates with humans, an earlier onset of the disease season may result in more cases with greater degrees of warming.

**Other vector-borne diseases:** Among studies projecting the risks of other vector-borne diseases (Carvalho et al. 2015, Ceccarelli and Rabinovich 2015, Domssa et al. 2016, Garza et al. 2014, Gonzalez et al. 2014, Kartashev et al. 2014, McIntyre et al. 2017, Medone et al. 2015, Ochieng et al. 2016), two projected risks for Chagas disease and leishmaniasis at 1.5°C and 2°C (Ceccarelli and Rabinovich 2015, Gonzalez et al. 2013). Overall, projections of other vector-borne diseases suggest climate change could increase or decrease future health burdens, with greater risks at higher degrees of warming.

**Discussion**

Detection and attribution studies indicate climate change is already adversely affecting human health (e.g. Ebi et al. 2017), indicating that dangerous anthropogenic interference with the climate system is occurring. Identifying the magnitude and pattern of risks under different transient and stabilization increases in SAT can help inform the level of ambition and timing of adaptation and mitigation strategies and policies.

This comprehensive review summarizes the growing number of projections of the health risks of climate change, showing that higher global and regional SATs are generally detrimental to a wide array of climate-sensitive health outcomes. The evidence suggests high agreement among most studies, with broadly similar estimated risks for a particular exposure. It also highlights that the diversity of baselines, scenarios, and climate and health models used in the studies preclude the possibility of quantifying health risks across many of them (e.g. conduct a meta-analysis) but that there would be significant benefits in doing so.
Higher ambient temperatures and humidity levels can place additional stress on individuals engaging in physical activity. Measures of heat stress, particularly the wet bulb globe temperature, were developed to monitor environmental conditions during work and exercise, to determine when heat exposure could be hazardous (NIOSH 2016). With continued exposure to high ambient temperatures, and without interventions to lower core body temperature, heat stress can progress through heat stroke to death (Hanna and Tait 2015). Characteristics of the individual (e.g. age, health status, and level of physical fitness), type of activity (e.g. degree of exertion), and other factors determine disease progression. Heat stress can be reduced through adaptation by modifying metabolic heat production or heat exchange associated with convection, radiation, or evaporation. Projections of the risks of heat stress and heat mortality in warming climates do not take into account these and other critical factors, leading to low confidence in estimates of how health burdens could change with climate change.

As temperatures and other weather variables continue to change, health models need to consider how to most appropriately represent temperature-related risks in what are now the tails of the exposure distribution (e.g. extreme temperature events). Assumptions about the shape of associations in the upper tails of what is now current exposure(s) were not always stated in the studies reviewed. Particularly for high temperatures, recent projections were often based on mathematical functions where the shape of the exposure-response curve is highly non-linear (Gasparrini et al 2015, WHO 2014). But some functions, such as natural cubic splines, are likely to become linear beyond the range of the observations, which means they may not provide accurate estimates of future risks (Rocklov and Ebi 2012). Linear assumptions can significantly affect the magnitude of projected heat-related mortality risks (Rocklov and Ebi 2012). Assumptions of linearity in earlier projections were common, although it is unlikely that heat-related mortality will increase linearly with higher temperature increases because of acclimatization and adaptation, including changes in the built environment (Astrom et al 2013, Dong et al 2015, Hajat et al 2014, Huynen and Martens 2015, Kingsley et al 2016, Li et al 2015, Marsha et al 2016, Martinez et al 2016, Vardoulakis et al 2014, Wang et al 2016, WHO 2014). Assumptions about the shape of the relationships in vector-borne disease projections were often unclear. Not accounting for non-linear responses to changing hazards means that projections could over- or underestimate risks, and may not account for surprises.

Therefore, as good practice, we recommend that studies projecting health risks from climate change state assumptions about the shape of associations assumed between exposure(s) and health outcomes at higher degrees of temperature change. This is important because the effectiveness of public health interventions to adapt to hotter temperatures will depend on the accuracy of estimates of health risks associated with future warming.

We also recommend that future projections report global and regional mean SAT changes to increase comparability across studies to understand the magnitude of the challenges that will likely need to be addressed, and to estimate when those temperature changes are likely to arise; the latter can inform the timing of when adaptation interventions will likely be necessary. Developing a set of common scenarios, combining climate projections under a range of emission pathways and multiple socioeconomic development pathways, would facilitate comparisons across studies.

Without reporting temperature change associated with modeling choices in studies, it is not readily apparent when projections cross important policy-relevant temperature thresholds that could increase potential harm to population health. Reporting temperature change would make the information from health projections much more useful to decision makers planning adaptations to manage health risks. By comparing different scenarios at each degree of temperature change, it would be useful to compare the outcomes under the same temperature change, but with different levels of economic development as expressed through the Shared Socioeconomic Pathways (Ebi 2014). For example, the degree of projected temperature change is similar under RCP4.5 in the year 2100 to under RCP8.5 in 2050; however, socioeconomic conditions (e.g. economic growth, population, technology, policies and institutions) will change. Therefore, exposure to climate-related hazards and adaptive capacity will differ in 2050 and 2100.

Reporting of time slices is also needed to provide insights into the urgency associated with developing adaptation interventions to protect health and into how quickly mitigation policies can reduce the magnitude of climate change to which individuals, communities, and health systems will need to adapt. In health systems, apart from planning infrastructure investments with long lifetimes, most adaptations focus on relatively short time scales, such as implementing early warning and response systems. Long-term adaptation constitutes a series of sequential short-term decisions within an iterative risk management framework (Ebi 2011, Hess et al 2012). Therefore, projections of the magnitude and pattern of health risks in, for example, 2030, can inform adaptation planning over the next decade, while projections of risks in 2050 can inform adaptation over the subsequent decades.

To inform studies projecting future health risks, it would be helpful for health researchers to develop scenarios of population health and health systems development over this century that can extend the climate change and development scenarios (e.g. Shared
Socioeconomic Pathways) (Ebi 2014, Sellers and Ebi 2017). Narratives and quantifications are needed at regional and global scales of how critical parameters affecting health could evolve under different development pathways, to improve the ability to quantify morbidity and mortality among different groups such as vulnerable people. These factors can include the extent to which health systems will be prepared to manage changing health burdens; inequities in health and income; and drivers traditionally outside the health sector, such as travel and tourism. These scenarios would support more robust projections of the magnitude and pattern of health risks associated with different degrees of regional and global changes in SAT, precipitation, sea level rise, and other variables, under different trajectories of population exposure and vulnerabilities. With this information, it would be possible to project the range of possible health benefits and risks associated with different policy choices to address climate change and its associated risks.

Scenarios also need to explicitly incorporate adaptation assumptions. For example, while planned adaptation to reduce impacts of heat on health (e.g. heat warning systems, air conditioning, monitoring and surveillance) can be effective (Anderson et al 2016, Toloo et al 2015, White et al 2017), the magnitude of risk reduction associated with specific measures is largely unknown (Deschenes 2014). Without incorporating estimates of the effectiveness of adaptation at various time slices and degrees of temperature change in studies, projected health risks are unlikely to accurately estimate the magnitude of the challenges to be managed. For example, assumptions of a constant increase in successful heat adaptation in projections of future heat health risks from climate change do not capture the complexity of regionally specific vulnerability factors and the non-linearity of climate responses, thereby significantly underestimating risks to health (Ebi et al 2016). Scenarios also need to consider limits to adaptation, such as physiological limits to acclimatization to higher temperatures.

Climate change and health vulnerability and adaptation assessments can provide a rich source of quantitative and qualitative data for planning appropriate adaptive responses to rapid climatic shifts (WHO 2013). Integration of information about nonlinear relationships associated with climate and health responses into future research and the application of iterative risk management approaches to prepare for impacts are needed to reduce risks of very severe impacts (Ebi et al 2016, Hess and Ebi 2016).

There are multiple sources of uncertainty in the analyses, including uncertainties in the climate models and greenhouse gas emission pathways, assumptions underlying health models, accuracy of the health models, extent of robust inclusion of adaptation, and others. We introduced another source of uncertainty by using the decade 2010–2019 as the baseline; we did this because of the challenges of different historic starting points for each GCM. This was not likely the largest source of uncertainty.

Conclusions

Overall, the health risks of a global mean SAT increase of 2°C above pre-industrial temperatures are projected to be greater than the risks for an increase of 1.5°C, with generally even higher risks at greater increases in SAT. The risks may be particularly elevated for heat-related morbidity and mortality, heat stress, ground-level ozone, and undernutrition. For vector-borne diseases, the risks are more variable because warmer temperatures may result in some regions becoming too hot and/or too dry for a vector. Future concentrations of particulate matter could increase or decrease, depending on emission assumptions and projected changes in precipitation. Despite the limitations, this review supports the ambition of rapidly reducing greenhouse gas emissions to increase the probability that health risks will stay within manageable boundaries.

The Paris Agreement is an important and possibly unique opportunity for the climate and health research enterprise to inform effective decisions to prepare for and manage the health risks of additional climate change, from local to international levels. Providing policy-relevant projections of the health risks of climate change will increase the possibilities of protecting and promoting population health, today and in the future.

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References

Alexeeff S E, Pfister G G and Nychka D 2016 A Bayesian model for quantifying the change in mortality associated with future ozone exposures under climate change Biometrics 72 281–8
Anderson G B, Olesen K W, Jones B and Peng R D 2016 Projected trends in high-mortality heatwaves under different scenarios of climate, population, and adaptation in 82 US communities Clim. Change 146
Arbuthnott K, Haat S, Heaviside C and Vardoulakis S 2016 Changes in population susceptibility to heat and cold over time: Assessing adaptation to climate change Environ. Health Glob. 15 S33
Astrom C, Orru H, Rocklov J, Strandberg G, Ebi K L and Forsberg B 2013 Heat-related respiratory hospital admissions in Europe in a changing climate: a health impact assessment BMJ Open 3 e001842
Banu S, Hu W B, Guo Y M, Hurst C and Tong S L 2014 Projecting the impact of climate change on dengue transmission in Dhaka, Bangladesh Environ. Int. 63 137–42
Belova O A et al 2017 Properties of the tick-borne encephalitis virus population during persistent infection of ixodid ticks and tick cell lines Ticks Tick Borne Dis. 8 895–906
Benmarhnia T et al 2014 Variability in temperature-related mortality projections under climate change Environ. Health Persp. 122 1293–8
Bouzid M, Colon-Gonzalez F J, Lung T, Lake I R and Hunter P R 2014 Climate change and the emergence of vector-borne diseases in Europe: case study of dengue fever BMC Public Health 14 281
Brown H E, Young A, Lega J, Androutsis T G, Schurich J and Comrie A 2015 Projection of climate change influences on US West Nile virus vectors Earth Interact. 19 1–18
Butterworth M K, Morin C W and Comrie A C 2017 An analysis of the potential impact of climate change on dengue transmission in the southeastern United States Environ. Health Persp. 125 579–95
Caminade C et al 2014 Impact of climate change on global malaria distribution Proc. Natl Acad. Sci. USA 111 3286–91
Campbell L P, Luther C, Moo-Llanes D, Ramsey J Y, Danis-Lozano R and Peterson A T 2015 Climate change influences on global distributions of dengue and chikungunya virus vectors Phil. Trans. R. Soc. B 370 20140135
Carvalho B M, Rangel E F, Ready P D and Vale M M 2015 Ecological niche modelling predicts southward expansion of lutzomyia (nyssomyia) flaviscutellata (diptera: Psychodidae: Phlebotominae), vector of leishmania (leishmania) amazonensis in South America, under climate change PLoS ONE 10 e0143282
Cecerelli S and Rabinovich J E 2015 Global climate change effects on Venezuela’s vulnerability to chagas disease is linked to the geographic distribution of five triatome species J. Med. Entomol. 52 1333–43
Chang H H, Hao H and Sarnat S E 2014 A statistical modeling framework for projecting future ambient ozone and its health impact due to climate change Atmos. Environ. 89 290–7
Chen C C, Jenkins E, Epp T, Waldner C, Curry P S and Soos C 2013 Climate change and West Nile virus in a highly endemic region of North America Int. J. Environ. Res. Pub. Health 10 3052–71
Chung Y et al 2017 Temporal changes in mortality related to extreme temperatures for 15 cities in northeast Asia: Adaptation to heat and maladaptation to cold Ann. J. Epidemiol. 185 907–15
Colón-Gonzalez F J, Fezzi C, Lake I R and Hunter P R 2013 The effects of weather and climate change on dengue PLoS Negl. Trop. Dis. 7 e2503
Cramer W et al 2014 Detection and attribution of observed impacts Climate Change 2014: Impacts, Adaptation, and vulnerability (Cambridge: Cambridge University Press) pp 979–1038
Descenes O 2014 Temperature, human health, and adaptation: a review of the empirical literature Energy Econ. 46 606–19
Dhingra R et al 2013 Spatially-explicit simulation modeling of ecological response to climate change: methodological considerations in predicting shifting population dynamics of infectious disease vectors Isprs. Int. Geo. Inf. 2 645–64
Dionisio K L et al 2017 Characterizing the impact of projected changes in climate and air quality on human exposures to ozone J. Environ. Sci. 29 260–70
Domka C, Sandor A D and Mihalca A D 2016 Climate change and species distribution: possible scenarios for thermophilic ticks in Romania Geospat. Health 11 151–6
Dong W H, Liu Z, Liao H, Tang Q H and Li X E 2015 New climate and socio-economic scenarios for assessing global human health challenges due to heat risk Clim. Change 130 505–18
Doyon B, Belanger D and Gosselin P 2008 The potential impact of climate change on annual and seasonal mortality for three cities in Quebec, Canada Int. J. Health Geogr. 7 23
Dunne J P, Stouffer R J and John J G 2013 Reductions in labour capacity from heat stress under climate warming Nat. Clim. Change 3 563–6
Ebi K L 2011 Climate change and health risks: Assessing and responding to them through ‘adaptive management’ Health Affair. 30 924–30
Ebi K L 2014 Health in the new scenarios for climate change research Int. J. Environ. Res. Pub. Health 11 30–46
Ebi K L, Hess J J and Iasken T B 2016 Using uncertain climate and development information in health adaptation planning Curr. Environ. Health Rep. 3 99–105
Ebi K L, Ogden N H, Semenza J C and Woodward A 2017 Detecting and attributing health burdens to climate change Environ. Health Persp. 850041
Fang Y, Mauzerall D L, Liu J, Fiore A M and Horowitz L W 2013 Impacts of 21st century climate change on global air pollution-related premature mortality Clim. Change 121 239–53
Fann N et al 2015 The geographic distribution and economic value of climate change-related ozone health impacts in the United States in 2030 J. Air Waste Manage. Assoc. 65 570–80
Feria-Arroyo T P et al 2014 Implications of climate change on the distribution of the tick vector ixodes scapularis and risk for Lyme disease in the Texas-Mexico transboundary region Parasite Vector 7 199
Fischer D, Thomas S M, Niemitz F, Reineking B and Beierkuhnlein C 2011 Projection of climatic suitability for aedes albopictus skuse (culicidae) in Europe under climate change conditions Glob. Planet Change 78 54–64
Fischer D et al 2013 Climate change effects on chikungunya transmission in Europe: Geospatial analysis of vector’s climatic suitability and virus temperature requirements Int. J. Health Geogr. 12 51
Garcia-Mendez F, Saari R K, Monier E and Selin N E 2015 US Air quality and health benefits from avoided climate change under greenhouse gas mitigation Environ. Sci. Technol. 49 7580–8
Garland R M et al 2015 Regional projections of extreme apparent temperature days in Africa and the related potential risk to human health Int. J. Environ. Res. Pub. Health 12 12577–604
Garza M, Arroyo T P F, Casillas E A, Sanchez-Cordero V, Rivaldi C I and Sarkar S 2014 Projected future distributions of vectors of trypanosoma cruzi in North America under climate change scenarios PLoS Neglect. Trop. Dis. 8 e2818
Gasparini A et al 2015 Mortality risk attributable to high and low ambient temperature: A multicountry observational study Lanecet 386 369–75
Gasparini A et al 2017 Projections of temperature-related excess mortality under climate change scenarios Lancet Planet Health 1 e360–7
Geels C et al 2015 Future premature mortality due to O3, secondary inorganic aerosols and primary PM10 in Europe—sensitivity to changes in climate, anthropogenic emissions, population and building stock Int. J. Environ. Res. Public Health 12 2837–69
Gonzalez C, Paz A and Ferro C 2014 Predicted altitudinal shifts and reduced spatial distribution of leishmania infantum vector species under climate change scenarios in Colombia Acta Trop. 129 83–90
Goto D et al 2016 Estimation of excess mortality due to long-term exposure to PM2.5 in Japan using a high-resolution model for present and future scenarios Atmos. Environ. 140 320–32
Goya Y, Li S S, Liu D L, Chen D, Williams G and Tong S L 2016 Projecting future temperature-related mortality in three largest Australian cities Environ. Pollut. 208 66–73
Hajat S, Vardoulakis S, Heaviside C and Eggen B 2014 Climate change effects on human health: Projections of temperature-related mortality for the UK during the 2020s, 2050s and 2080s J. Epidemiol. Commun. Health 68 641–8
Hanna E G, Kjellstrom T, Bennett C and Dear K 2011 Climate change and rising heat: Population health implications for working people in Australia Asia Pac. J. Publ. Health 23 14–26

Hanna E G and Tait P W 2015 Limitations to thermoregulation and acclimatization challenge human adaptation to global warming Int. J. Environ. Res. Public Health 12 8034–74

Harrigan R J, Thomasen H A, Buermann W and Smith T B 2014 A continental risk assessment of West Nile virus under climate change Glob. Change Biol. 20 2417–25

Hasegawa T, Fujimori S, Takahashi K, Yokohata T and Masui T 2011 Regional warming and emerging vector-borne zoonotic dirofilariosis in the Russian Federation, the dengue vector mosquito aedes albopictus respond to climate change in the metropolitan area of Skopje BMC Public Health 16 407

Huang C R, Barnett A G, Wang X M and Tong S L 2012 The global distribution of aedes aegypti: spatial modelling using climate warming scenario-based integrated environmental health impact assessment Int. J. Environ. Res. Publ. Health 12 3293–320

IPCC (Intergovernmental Panel on Climate Change) 2007 Data Distribution Center (www.ipcc-data.org/sim/gcm_global/index.html) (Accessed: 13 October 2017)

IPCC (Intergovernmental Panel on Climate Change) 2013 Summary for Policymakers Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change ed T F Stocker, D Qin, G K Plattner, M Tignor, S K Allen, J Boschung, A Nauels, Y Xia, V Bex and P M Midgley (Cambridge: Cambridge University Press) p 29

Ishida H et al 2014 Global-scale projection and its sensitivity analysis of the health burden attributable to childhood undernutrition under the latest scenario framework for climate change research Environ. Res. Lett. 9 064014

Jackson J E et al 2010 Public health impacts of climate change in Washington state: Projected mortality risks due to heat events and air pollution Clim. Change 102 159–86

Jia P F, Chen X, Chen J, Lu L, Liu Q Y and Tan X Y 2017 How does the dengue vector mosquito aedes albopictus respond to global warming? Parasite Vector 10 140

Karasheva V et al 2014 Regional warming and emerging vector-borne zoonotic dirofilariosis in the Russian Federation, Ukraine, and other post-Soviet states from 1981–2011 and projection by 2030 Biomed. Res. Int. 2014 858936

Kendrovski V, Ramic I, Martinez G S, Wolf T, Paukovic E and Menne B 2017 Quantifying projected heat mortality impacts under 21st-century warming conditions for selected European countries Int. J. Environ. Res. Public Health 14 729

Khormi H M and Kumar L 2014 Climate change and the potential global distribution of aedes aegypti: spatial modelling using geographical information system and climex Geospatial Health 8 405–15

Khormi H M and Kumar L 2016 Future malaria spatial pattern based on the potential global warming impact in south and southeast Asia Geospatial Health 11 290–8

Kingsley S L, Eliot M N, Gold J, Vanderslice R R and Wellenius G A 2016 Current and projected heat-related morbidity and mortality in Rhode Island Environ. Health Persp. 124 460–7

Kjellstrom T, Lemke B and Otto M 2013 Mapping occupational heat exposure and effects in south-east Asia: Ongoing time trends 1980–2011 and future estimates to 2050 Ind. Health 51 56–67

Kjellstrom T, Lemke B and Otto M 2017 Climate conditions, workplace heat and occupational health in south-east Asia in the context of climate change WHO South East Asia J. Public Health 11 144–50

KMN1 2013 Global mean temperature of CMIP5 monthly historical and RCP experiments (https://climexp.knmi.nl/CMIP5/Tglobal/index.cgi) (Accessed: 13 October 2017)

Kwak J et al 2014 Future climate data from RCP 4.5 and occurrence of malaria in Korea Int. J. Environ. Res. Public Health 11 10587–605

Laporta G E et al 2015 Malaria vectors in South America: current and future scenarios Parasite Vectors 8 426

Lee Y J, Lee S H, Hong S-C and Kim H 2017 Projecting future summer mortality due to ambient ozone concentration and temperature changes Atmos. Environ. 156 88–94

Levi T et al 2015 Accelerated phenology of blacklegged ticks under climate warming Phil. Trans. R. Soc. B 370

Li T T et al 2015 Heat-related mortality projections for cardiovascular and respiratory disease under the changing climate in Beijing, China Sci. Rep. UK 5 11441

Li T T et al 2016 Aging will amplify the heat-related mortality risk under a changing climate: projection for the elderly in Beijing, China Sci. Rep. UK 6 28161

Likhvar V N et al 2015 A multi-scale health impact assessment of air pollution over the 21st Century. Sci. Total Environ. 514 439–49

Liu-Heermansson J et al 2016 Climate change and aedes vectors: 21st century projections for dengue transmission in Europe Ebiomedicine 7 267–77

Liu J C et al 2016 Future respiratory hospital admissions from wildfire smoke under climate change in the Western US Environ. Res. Lett. 11 124018

Marsha A, Sam S, Heaton M, Monaghan A and Wilhelmi O 2016 Influences of climatic and population changes on heat-related mortality in Houston, Texas, USA Clim. Change 146 1

Martinez G S et al 2016 Projected heat-related mortality under climate change in the metropolitan area of Skopje BMC Public Health 16 407

Matthews T K, Wilby R L and Murphy C 2017 Communicating the deadly consequences of global warming for human heat stress Proc. Natl Acad. Sci. USA 114 3861–6

McIntyre S, Rangel F E, Ready P D and Carvalho B M 2017 Species-specific ecological niche modelling predicts different range contractions for lutzomyia interimedia and a related vector of leishmania braziliensis following climate change in South America Parasite Vector 10 157

Medone P, Ceccarelli S, Parham P E, Figuera A and Rabinovich J E 2015 The impact of climate change on the geographical distribution of two vectors of chagas disease: Implications for the force of infection Phil. Trans. R. Soc. Biol. 370 20130560

Monaghan J A, Moore S M, Sampson K M, Beard C B and Eisen R J 2015 Climate change influences on the annual onset of lyme disease in the United States Tick-Borne Dis. 6 615–22

Morin C W and Comrie A C 2013 Regional and seasonal response of a West Nile virus vector to climate change Proc. Natl Acad. Sci. USA 110 15620–5

Mweya C N, Kimera S I, Stanley G, Misinzo G and Mboera L E G 2014 Future climate data from RCP 4.5 and occurrence of malaria in Tanzania PloS ONE 11 e0162049

Myers S S et al 2017 Climate change and global food systems: Potential impacts on food security and undernutrition Annu. Rev. Publ. Health 38 259–77

NIOSH 2016 NIOSH Criteria for a Recommended Standard: Occupational Exposure to Heat and Hot Environments (Washington DC: NIOSH)

Ochieng A O et al 2016 Ecological niche modelling of Rift Valley fever virus vectors in Baringo, Kenya Infect Ecol. Epidemiol. 6 32322
Ogden N H, Milka R, Caminade C and Gachon P 2014a Recent and projected future climatic suitability of North America for the asian tiger mosquito aedes albopictus Parasite Vector 7 532
Ogden N H, Radojevic M, Wu X T, Duveiller V R, Leighton P A and Wu J H 2014b Estimated effects of projected climate change on the basic reproductive number of the lyme disease vector ixodes scapularis Environ. Health Persp. 122 631–8
Oleson K W, Anderson G B, Jones B, McGinnis S A and Sanderson B 2015 Avoided climate impacts of urban and rural heat and cold waves over the US using large climate model ensembles for RCP8.5 and RCP4.5 Clim. Change 2015 525–41
Ortu H, Andersson C, Ebi K L, Langner J, Astrom C and Forsberg B 2013 Impact of climate change on ozone-related mortality and morbidity in Europe Eur. Respir. J. 41 285–94
Ortu H, Ebi K L and Forsberg B 2017 The interplay of climate change and air pollution on health Curr. Environ. Health Rep. 4 304–13
Pal J S and Eltahir E A B 2015 Future temperature in southwest Asia projected to exceed a threshold for human adaptability Nat. Clim. Change 6 197
Petkova E P, Horton R M, Bader D A and Kinney P L 2013 Projected heat-related mortality in the US urban northeast Int. J. Environ. Res. Pub. Health 10 6734–47
Petkova E P et al 2017 Towards more comprehensive projections of urban heat-related mortality: Estimates for New York City under multiple population, adaptation, and climate scenarios Environ. Health Persp. 125 47–55
Physack W, Cope M and Lee S 2014 The impact of climate change on ozone-related mortality in Sydney Int. J. Environ. Res. Pub. Health 11 1034–48
Porrett D et al 2013 Effects of global changes on the climatic niche of the tick ixodes ricinus inferred by species distribution modelling Parasite Vector 6 271
Proestos Y, Christophides G K, Erguler K, Tanarhte M, Waldock J and Lelieveld J 2015 Present and future projections of habitat and seasonal risk of transmission changes in Africa, due to the climate impact of land use change using coupled model intercomparison project phase 5 earth system models Geospatial Health 10 16–73
Ren Z et al 2016 Predicting malaria vector distribution under climate change scenarios in China: Challenges for malaria elimination Sci. Rep. 6 20604
Rocklöf J and Ebi K L 2012 High dose extrapolation in climate change projections of heat-related mortality J. Agric. Biol. Environ. St. 17 461–75
Ryan S J, Carlson C J, Mordecai E A and Johnson L R 2017 Climate change drives uncertain global shifts in potential distribution and seasonal risk of aedes-transmitted viruses bioRxiv 172221
Schwartz J D et al 2015 Projections of temperature-attributable premature deaths in 209 US cities using a cluster-based poisson approach Environ. Health Glob. 14 85
Sellers S and Ebi K L 2017 Climate change and health under the shared socioeconomic pathway framework Int. J. Environ. Res. Public Health 15 3
Semakula H M et al 2017 Prediction of future malaria hotspots under climate change in sub-saharan Africa Clim. Change 143 415–28
Semenza J C, Tran A, Espinosa L, Sudre B, Domanovic D and Paz S 2016 Climate change projections of West Nile virus infections in Europe: implications for blood safety practices Environ. Health Glob. 15 528
Sheffield P E, Herrera J G R, Lemke B, Kjellstrom T and Romero L E B 2013 Current and future heat stress in Nicaraguan work places under a changing climate Ind. Health 51 123–7
Sheridan S C and Dixon P G 2016 Spatiotemporal trends in human vulnerability and adaptation to heat across the United States Anthroposene 20 61–73
Sherwood S C and Huber M 2010 An adaptability limit to climate change due to heat stress Proc. Natl. Acad. Sci. USA 107 9532–5
Silva R A et al 2016 The effect of future ambient air pollution on human premature mortality to 2100 using output from the accmip model ensemble Atmos. Chem. Phys. 16 9847–62
Silva R A et al 2017 Future global mortality from changes in air pollution attributable to climate change Nat. Clim. Change 7 845–845
Simon J A et al 2014 Climate change and habitat fragmentation drive the occurrence of borrelia burgdorferi, the agent of lyme disease, at the northeastern limit of its distribution Evol. Appl. 7 750–64
Smith K R et al 2014 Human health: Impacts, adaptation, and co-benefits In IPCC Working Group II Assessment and Review 5
Song Y Z, Ge Y, Wang J F, Ren Z P, Liao Y L and Peng H J 2016 Spatial distribution estimation of malaria in northern China and its scenarios in 2020, 2030, 2040 and 2050 Malaria J. 15 345
Springmann M et al 2016 Global and regional health effects of future food production under climate change: a modelling study Lancet 387 1937–46
Sun J, Fu J S, Huang K and Gao Y 2015 Estimation of future PM2.5- and ozone-related mortality over the continental United States in a changing climate: an application of high-resolution dynamical downscaling technique J. Air Waste Manag. Assoc. 65 611–23
Tagaris E, Sotiropoulos R F P, Sotiropoulos A, Spanos I, Milonas P and Michaelakis A 2017 Climate change impact on the establishment of the invasive mosquito species (IMS) Perspectives on Atmospheric Sciences ed T Karacostas, A Bais and P T Nastos (Cham: Springer) pp 689–94
Takakura J et al 2017 Cost of preventing workplace heat-related illness through worker breaks and the benefit of climate-change mitigation Environ. Res. Lett. 12 064010
Tainio M, Juda-Rezler K, Reizner M, Warchalowski A, Trapp W and Skoták K 2013 Future climate and adverse health effects caused by fine particulate matter air pollution: Case study for poland Reg. Environ. Change 13 705–13
Teurlai M et al 2015 Socio-economic and climate factors associated with dengue fever spatial heterogeneity: a worked example in New Caledonia PLoS Negl. Trop. Dis. 9 e0004211
Tjaden N B, Suk J E, Fischer D, Thomas S M, Beierkuhnlein C and Semenza J C 2017 Modelling the effects of global climate change on chikungunya transmission in the 21(st) century Sci. Rep. 7 3813
Toloso G, FitzGerald G, Aitken P, Verral K and Tong S L 2013 Evaluating the effectiveness of heat warning systems: systematic review of epidemiological evidence Int. J. Public Health 58 667–81
Tompkins A M and Caporaso L 2016 Assessment of malaria transmission changes in Africa, due to the climate impact of land use change using coupled model intercomparison project phase 5 earth system models Geospatial Health 11 16–73
United Nations 2015 Paris Agreement (http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf) (Accessed: 13 October 2017)
Vardoulakis S, Dear K, Hajat S, Heaviside C, Eggen B and Tompkins A M and Caporaso L 2016 Assessment of the effects of climate change on heat-and cold-related mortality in the United Kingdom and Australia Environ. Health Persp. 122 1285–92
Vicedo-Cabrera A M et al 2017 A multi-country analysis on potential adaptive mechanisms to cold and heat in a changing climate Environ. Int. 111 239–46
Voorhees A S et al 2011 Climate change-related temperature impacts on warm season heat mortality: a proof-of-concept methodology using BenMAP Environ. Sci. Technol. 45 1450–7
Wang L, Huang J B, Luo Y, Yao Y and Zhao Z C 2015 Changes in extremely hot summers over the global land area under various warming targets PLoS ONE 10 e0130660
Wang Y, Shi L H, Zanobetti A and Schwartz J D 2016 Estimating and projecting the effect of cold waves on mortality in 209 US cities Environ. Int. 94 141–9
Weinberger K R, Haykin L, Eliot M N, Schwartz J D, Gasparrini A and Wellenius G A 2017 Projected temperature-related deaths in ten large US metropolitan areas under different climate change scenarios Environ. Int. 107 196–204

White J R et al 2017 Evaluation of a novel syndromic surveillance query for heat-related illness using hospital data from Maricopa County, Arizona, 2015 Public Health Rep. 132 31s–39s

Williams C R, Mincham G, Ritchie S A, Viennet E and Harley D 2014 Bivomic response of aedes aegypti to two future climate change scenarios in far North Queensland, Australia: implications for dengue outbreaks Parasite Vector 7 144

Williams C R, Mincham G, Faddy H, Viennet E, Ritchie S A and Harley D 2016 Projections of increased and decreased dengue incidence under climate change Epidemiol. Infect. 144 3091–100

Williams H W, Cross D E, Crump H L, Drost C J and Thomas C J 2015 Climate suitability for European ticks: Assessing species distribution models against null models and projection under AR5 climate Parasite Vector 8 440

Wilson A, Reich B J, Nolte C G, Spero T L, Hubbell B and Rappold A G 2017 Climate change impacts on projections of excess mortality at 2030 using spatially varying ozone-temperature risk surfaces J. Expo. Sci. Environ. Epidemiol. 27 118–24

World Health Organization 2013 Protecting Health from Climate Change: Vulnerability and Adaptation Assessment (Geneva: World Health Organization)

World Health Organization 2014 Quantitative Risk Assessment of the Effects of Climate Change on Selected Causes of Death, 2030s and 2050s (Geneva: World Health Organization)

World Health Organization 2016 World Malaria Report (Geneva: World Health Organization)

Wu J Y et al 2014 Estimation and uncertainty analysis of impacts of future heat waves on mortality in the eastern United States Environ. Health Persp. 122 10–6

Yamana T K, Bombly A and Eltaher E A B 2016 Climate change unlikely to increase malaria burden in west Africa Nat. Clim. Change 6 1009

Zhao Y, Sultan B, Vautard R, Braconnot P, Wang H J J and Ducharme A 2016 Potential escalation of heat-related working costs with climate and socioeconomic changes in China Proc. Natl Acad. Sci. USA 113 4640–5