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To cite this article: Sarah Chapman *et al* 2022 *Environ. Res. Lett.* **17** 074028

ENVIRONMENTAL RESEARCH
LETTERS

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OPEN ACCESS

RECEIVED
4 March 2022

REVISED
8 June 2022

ACCEPTED FOR PUBLICATION
21 June 2022

PUBLISHED
4 July 2022

LETTER

Past and projected climate change impacts on heat-related child mortality in Africa

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Keywords: climate change, health impacts, heat stress, child mortality, Africa

Supplementary material for this article is available online

Abstract

Children (<5 years) are highly vulnerable during hot weather due to their reduced ability to thermoregulate. There has been limited quantification of the burden of climate change on health in sub-Saharan Africa, in part due to a lack of evidence on the impacts of weather extremes on mortality and morbidity. Using a linear threshold model of the relationship between daily temperature and child mortality, we estimated the impact of climate change on annual heat-related child deaths for the current (1995–2020) and future time periods (2020–2050). By 2009, heat-related child mortality was double what it would have been without climate change; this outweighed reductions in heat mortality from improvements associated with development. We estimated future burdens of child mortality for three emission scenarios (SSP119, SSP245 and SSP585), and a single scenario of population growth. Under the high emission scenario (SSP585), including changes to population and mortality rates, heat-related child mortality is projected to double by 2049 compared to 2005–2014. If 2050 temperature increases were kept within the Paris target of 1.5 °C (SSP119 scenario), approximately 4000–6000 child deaths per year could be avoided in Africa. The estimates of future heat-related mortality include the assumption of the significant population growth projected for Africa, and declines in child mortality consistent with Global Burden of Disease estimates of health improvement. Our findings support the need for urgent mitigation and adaptation measures that are focussed on the health of children.

1. Introduction

Climate change negatively affects human health through exposure to extreme weather and climate events, including the direct effect of high temperatures on heat stress, and indirect effect of temperature on infectious disease and food safety and security (Sheffield and Landrigan 2011, Rylander *et al* 2013). High temperatures are responsible for a significant burden of disease. The global estimate of heat-related mortality across all ages is approximately 500 000 deaths per year (Zhao *et al* 2021). Temperatures are already increasing in Africa, by between 0.2 °C and 0.4 °C per decade since 1980 (Trisos *et al* 2022). As temperatures continue to rise with climate change, heat deaths are expected to increase.

Children under five years old are especially vulnerable to the impacts of heat exposure (Helldén *et al* 2021). Very young children have a limited ability to thermoregulate (Sheffield and Landrigan 2011, Rylander *et al* 2013, Son *et al* 2017). Children in low-income settings with high temperatures are particularly vulnerable to heat due to pre-existing burdens of infection and undernutrition, poor healthcare systems, and dwellings that do not provide sufficient protection from the heat (Sheffield and Landrigan 2011, Rylander *et al* 2013). In high-income countries, heat-related deaths are largely restricted to deaths in older persons. In low-income settings, high temperatures are shown to increase acute mortality in children and young adults, representing a considerable burden in terms of years of life lost (Sewe *et al* 2018). Due to limitations associated with both health and environmental data, there has been little observational research in low-income and middle income countries on heat impacts, particularly in children (Basu *et al* 2015, Green *et al* 2019, Berrang-Ford *et al* 2021).

Better understanding how child mortality could be affected by climate change is vital for ensuring prioritization of health in national adaptation programmes. The future impacts of climate change on child mortality have previously been quantified for malnutrition and diarrhoeal disease (World Health Organization 2014) but not for heat-related mortality. Countries in Africa are set to undergo major development and demographic changes in the coming decades, with the potential to ameliorate or amplify future climate change impacts.

The aim of this study is to estimate the impact of climate change on annual heat-related child deaths for the current (1995–2020) and future time periods (2020–2050) in Africa, using published estimates of the relationship between ambient temperature and acute mortality in selected populations in Africa. First, we undertook an attribution study to quantify heat-related child mortality due to climate change in Africa over the period 1995–2020. We use observed population growth and the reductions in child mortality rate (due to improvements in health services, disease control, and the social determinants of health). We then conduct a comparative risk assessment to project the numbers of heat-related child deaths that occur in future decades (2020–2050) under low, medium, and high emissions scenarios (SSP119, 245, and 585; Meinshausen *et al* 2020), considering future population growth and the continued decline in child mortality rates. As there is very limited epidemiologic information available on the relationship between temperature and mortality in children in African countries, we use published coefficients from two studies to represent high and low bounds of heat-related mortality burdens for the continent. This work, therefore, provides indicative estimates of impacts. Despite the obvious limitations in basing estimates for Africa on studies in two locations, we believe providing an indicative first estimate of the scope of the issue is an important step in drawing attention to the problem of heat-related mortality in children, and the need for further research in this area.

2. Methods

We attributed heat deaths in children in Africa to anthropogenic emissions using the Detection and Attribution Climate Model Intercomparison (DAMIP) experiment of Coupled Model Intercomparison Project Phase 6 (CMIP6). This method has been used previously to estimate that a third of all heat-deaths in the period 1991–2018 can be attributed to climate change globally (Vicedo-Cabrera *et al* 2021). Attributing observed changes in health outcomes to climate change can be difficult as key health determinants also change over decadal scales (Ebi *et al* 2017). In this study, we have made a first estimate of the impact of climate change on heat-related child mortality in the present day and future, using CMIP6 climate scenarios, population and mortality projections, and published heat-mortality relationships in Africa.

2.1. Description of observed climate change and counterfactual datasets

We attributed heat-mortality to climate change by comparing two climate change scenarios, one corresponding to the historical (factual) climate, and an alternative (counterfactual) that corresponds to a world without anthropogenic climate change. The scenarios are from the DAMIP experiment of CMIP6, designed to distinguish the climate impacts of different forcings (O'Neill *et al* 2016). For the factual scenario, we used mean daily air temperature from 'historical' climate simulations from 1995 up to 2014, merged with SSP245 for 2015–2020, because 2015 is the start of the future simulation. These simulations are driven by natural and anthropogenic forcings; and are designed to represent actual historical climate. The corresponding counterfactual scenario is from the 'hist-nat' experiment, where only natural forcings (no anthropogenic greenhouse gases) were considered. Thus, the difference between the 'hist-nat' and 'historical' experiments quantifies the impact of anthropogenic forcings on the climate in Africa. Thirteen climate models were used in the analysis (see supplementary material table 1).

2.2. Description of the present-day population and mortality datasets

We used the gridded (1 km^2 resolution) WorldPop under-5 population data (WorldPop and Center for International Earth Science Information Network 2018) and national under-5 all-cause mortality rates from UNICEF (UNICEF Data 2019). 2000 is the earliest year for which age-structured, gridded population data are available, which is why we limited our historical analysis to 1995–2020. The mortality data were available as country totals and we mapped child

Table 1. Climate, population and mortality data for attribution study.

Data	Time period		
	1995–2020 (25 years)		
Climate	1995–2004	2005–2014	2015–2020
Population	2000	2010	2019
Mortality	2000	2010	2019

mortality values to individual grid cells using the population distribution for each time point (figure S1). The mortality data were available as yearly totals and daily all-cause mortality from equation (1) was calculated as annual all-cause mortality divided by 365.

The time periods of the datasets used in the attribution study are shown in table 1. For the first time period, population and mortality data from the middle of the period were used. For the 2015–2020 period, we used the most recent population and mortality data available, which was for 2019.

2.3. Description of the scenario data

To estimate future heat-related child mortality from 2020–2050, we used three scenarios of climate change (SSP119, SSP245 and SSP585), and one scenario of population growth and one scenario of child mortality which assumes that the current declines in child mortality rates will continue. SSP119 is the scenario most likely to achieve the 1.5 °C target under the Paris Agreement; SSP585 is a high fossil-fuel emission scenario; and SSP245 is a middle-of-the-road emission scenario (Meinshausen *et al* 2020). From the CMIP6 climate models, we obtained daily average temperature for each day between 2020 and 2050. For population and mortality data, we used information from the middle of the decade (i.e. the 2020–2029 period used 2025 population and mortality data).

For future populations (see figure S2), we used the SSP2 (middle-of-the-road) population projection (KC and Lutz 2017). We obtained age-structured country totals from the Wittgenstein Centre (Wittgenstein Centre for Demography and Global Human Capital 2018).

For future all-cause mortality, we used the Global Burden of Disease (GBD) reference scenario (Foreman *et al* 2018, Global Burden of Disease Collaborative Network 2020). We chose this projection because it is an evidence-based and plausible projection of health futures in Africa and because of the large number of modelled causes of death (Foreman *et al* 2018). The GBD reference scenario tends to give lower future all-cause mortality than the World Health Organization projections. The impact of lower all-cause mortality would be a lower absolute number of heat-related deaths. As the GBD projections only extend to 2040, we extrapolated to 2050 using the trend from 2020–2040 and a second-order polynomial (figure S2). This was applied on a country-by-country basis.

Future population and mortality data were distributed within countries according to the distribution of population in 2019. Migration within and between countries was not included due to lack of any demographic scenarios. Africa is likely to undergo significant urbanisation which may in fact increase local temperature exposures for urban populations. Alternatively, large scale movement to cooler climates would lead to an over-estimate of the modelled heat mortality. Overall, future population movement and its effect on heat exposures is highly uncertain.

Future population and mortality projections were adjusted using the 2000 and 2010 population and mortality data, respectively, and the linear-scaling method (see supplementary material for further details).

2.4. Description of the health impact model

We quantified the heat-related child (under-5) mortality in each grid cell in each individual climate model using the following equation (Hajat *et al* 2014):

$$\mathrm{DAT} = \frac{\mathrm{Pop}_{\mathrm{fut}}}{\mathrm{Pop}_{\mathrm{base}}} \times \frac{\mathrm{DM}}{e^{(b \times T_{\mathrm{d}} - \mathrm{Thres})}} \times \left(e^{(b \times T_{\mathrm{d}} - \mathrm{Thres})} - 1\right) \tag{1}$$

where DAT = daily attributable deaths due to temperature, DM = daily average mortality from all causes, T_{d} = daily average temperature, b = coefficient of the exposure-risk relationship, thres = threshold above which temperature mortality impacts occur. Under 5 population in the year 2000 was used as the base population ($\mathrm{Pop}_{\mathrm{base}}$). $\mathrm{Pop}_{\mathrm{fut}}$ refers to future under 5 population.

The coefficient, *b*, and the threshold are from two published time-series regression studies in Ghana and Kenya (Azongo *et al* 2012, Egondi *et al* 2012). We used the coefficient from both studies, and present our results as a range. Both studies used spline functions to flexibly model the functional form the relationship between temperature and mortality. These relationships showed no obvious non-linearity, which is why we have used a linear-threshold model here. The study in Kenya was based on 5 years of data, while the study in Ghana was based on 15 years of data (Azongo *et al* 2012, Egondi *et al* 2012). Limitations common to all epidemiological studies include missing data, and limited data on time varying confounding factors (Azongo *et al* 2012, Egondi *et al* 2012).

Both studies used the 75th percentile of local daily average temperature as the heat threshold above which risk of death increases linearly as temperatures rise; therefore, we assumed the 75th percentile of the temperature distribution unique to each grid cell to model localised heat thresholds. There is some variation in the threshold temperatures at which mortality impacts occur between populations (Hajat and

Kosatky 2010). However, applying the same threshold percentile across the region is a reasonable approximation that has been used in other studies (Honda *et al* 2014). There is also often consistency in percentile based thresholds across locations (Martínez-Solanas *et al* 2021). The 75th percentile is towards the lower end of the percentile thresholds usually used for heat-mortality relationships. A higher threshold would result in a lower absolute number of deaths.

Exposure effects were based on lags of 0 and 1 day, which were demonstrated to be the critical periods of exposure for heat in the studied populations (Sheffield *et al* 2018, Schinasi *et al* 2020).

The temperature threshold was calculated from the 1995–2010 period of the historical run from each individual model. This period was chosen as it encompasses the time periods used in the epidemiology studies. The work in Ghana and Kenya found that mortality increased linearly by 0.61% and 1.0% respectively for each 1 °C increase in daily average temperature above the threshold. In other words, effect estimates were based on linear-threshold models. These values were converted into the coefficient, *b,* using the following equation:

$$b = \ln\left(\frac{\%\text{increase per } 1\,^\circ\text{C}}{100} + 1\right) \quad (2)$$

where *b* represents just the linear portion of the temperature-mortality relationship characterised in the two studies. We calculated heat-related child mortality using the coefficients from both studies, and present the results as a range. There are limitations in using functions from only two locations in Africa, but we have developed this model using the best information available at this time. There are other studies available that examine heat related child mortality in Africa, but the two used here are the only ones that use consistent methods to quantify the acute temperature-mortality relationships in children in Africa. Due to differences in methods, it would not be straightforward to combine information from the other African studies, i.e. Scovronick *et al* (2018) uses maximum temperatures rather than mean and Mrema *et al* (2012) uses monthly temperatures rather than daily.

Prior to calculating mortality, all climate models were bias corrected (see below), and all input data sets (including population and mortality datasets) were regridded to a 0.5° × 0.5° resolution, the most common resolution of the input CMIP6 models.

2.5. Decomposition of mortality into components

We used the method of Das Gupta to decompose the contribution of changes in climate, population, and all-cause mortality rate to changes in heat-related child mortality (1993). To calculate the population, mortality and exposure (climate) effect, we used the following equations (Das Gupta 1993):

$$\text{Population effect:}\,(p-P)\left[\frac{me+ME}{3}+\frac{mE+Me}{6}\right] \quad (3)$$

$$\text{Mortality effect:}\,(m-M)\left[\frac{pe+PE}{3}+\frac{pE+Pe}{6}\right] \quad (4)$$

$$\text{Exposure effect:}\,(e-E)\left[\frac{pm+PM}{3}+\frac{pM+Pm}{6}\right] \quad (5)$$

where *p, m* and *e* refer to population $\left(\frac{\text{Pop}_{\text{fut}}}{\text{Pop}_{\text{base}}}\text{ from equation (1)}\right)$, total all-cause under-5 mortality (DM from equation (1)), and exposure to high temperatures respectively $\left(\frac{\left(e^{(b\times T_{\text{d}}-\text{Thres})}-1\right)}{e^{(b\times T_{\text{d}}-\text{Thres})}}\text{ from equation (1)}\right)$, and the lowercase refers to the historical (baseline) value and upper case refers to the future value.

2.6. Bias-correction of climate model data

Daily average temperature from all CMIP6 climate models (historical, hist-nat and future) were bias-corrected using the linear-scaling method with monthly correction factors (Teutschbein and Seibert 2012) and the Climatic Research Unit (CRU) TS4.0 gridded climate dataset (Harris 2019); 1970–1989 was the reference period for bias-correction.

3. Results

3.1. Present day climate change impacts on temperature

The impact of climate change on average temperatures in Africa, 1995–2020, is shown in figure 1. The ensemble mean of the CMIP6 models is cooler for the hist-nat (without anthropogenic climate change) scenario than the historical (with climate change) scenario. The average temperature increases over time in the historical scenario, while it stays relatively stable in the hist-nat scenario. The CRU observational data also shows this trend of increasing temperature over time, and is of a similar magnitude to the increase in temperature in the CMIP6 ensemble mean. The increasing temperature trends over time in Africa are well documented in the literature (Trisos *et al* 2022).

3.2. Current heat-related child mortality due to climate change

Heat-related child mortality for the historical and hist-nat scenarios for the periods 1995–2004 and 2011–2020 are shown in figure 2. Between

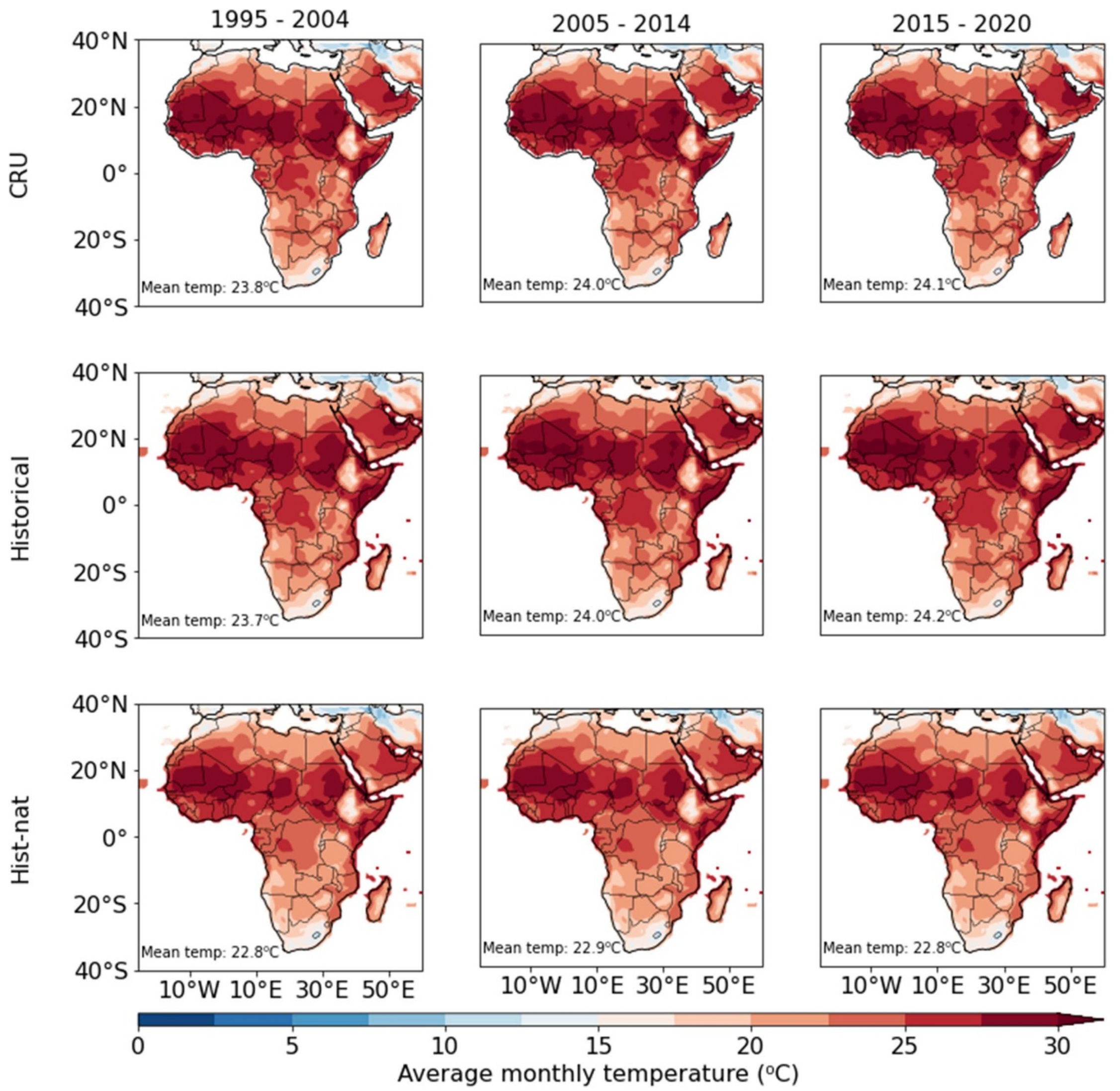

Figure 1. Average monthly temperature in Africa from 1995 to 2020, for the CRU observational dataset (row 1), the CMIP6 ensemble mean for the historical scenario (row 2) and the hist-nat scenario (row 3).

1995 and 2004, the CMIP6 ensemble mean heat-related child mortality in Africa was approximately 7000–11 000 deaths per year, depending on whether a lower (coefficient = 0.61) or higher (coefficient = 1.0) sensitivity to heat was used. Without climate change, this would have been approximately 4000–6000 deaths per year. In the 2011–2020 decade, with climate change, these numbers increase dramatically to approximately 12 000–19 000 deaths per year, depending on whether low or high sensitivity to heat was used. Without climate change, this would have been approximately 5000–8000 deaths per year. From 2009 onwards, heat-related child mortality with climate change was double what it would have been without climate change. Data for each country in Africa are presented in supplementary material table S2.

We decomposed the overall change in total heat-related child mortality from 1995 to 2004 to the recent decade of 2011–2020 into contributions from population growth, declining all-cause mortality rates, and climate change (figure 3(A), see section 2 for details). Population growth (figure 3(A)) meant that the total number of heat-related child deaths increased over time, even without climate change (figure 2, panel (A), white bars), and it was the largest contributor to the increase in total heat-related child mortality. Declining all-cause mortality rates (figure 3) mean that without climate change, the rate of heat-related child mortality (figure 2, panel (B), white bars) would have declined over time. However, these potential gains were outweighed by the impact of rising temperatures from climate change (figure 3). These conclusions were the same when assuming a higher sensitivity to heat, with higher absolute numbers of child deaths (coefficient = 1.0, see figure S3).

Figure 3, panel (B), shows how population growth, declining all-cause mortality rates, and climate change are projected to contribute to changes in heat-related child mortality in the 2040s relative

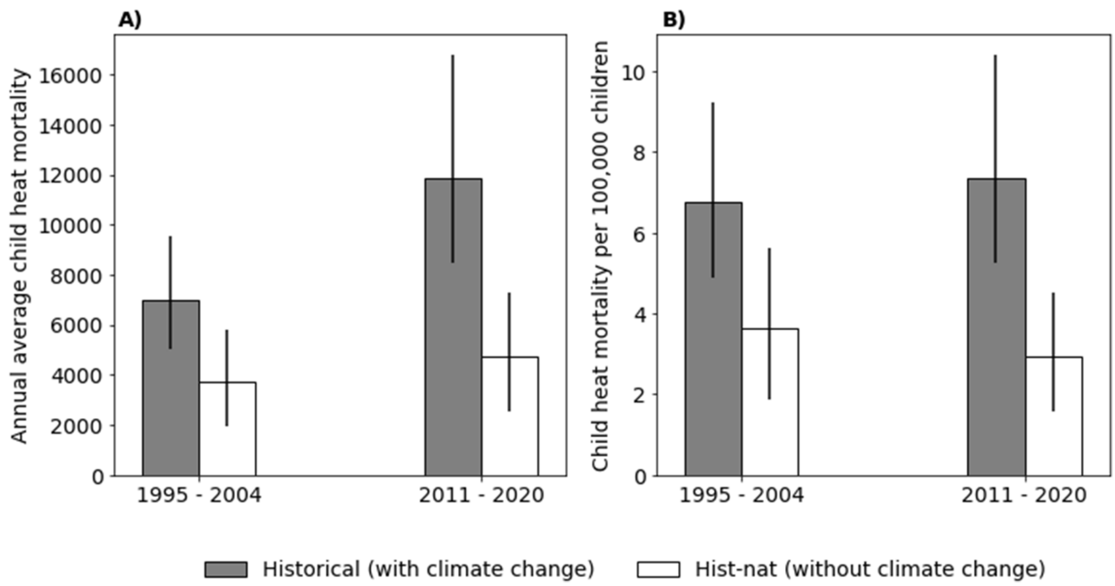

Figure 2. Heat-related child (under-5) mortality from 1995–2004 to 2011–2020 (A) annual average mortality in Africa over the decade, (B) annual average mortality per 100 000 children in Africa over the decade. Bars show 5th and 95th percentile from CMIP6 ensemble. Based on lower sensitivity to heat (coefficient = 0.61).

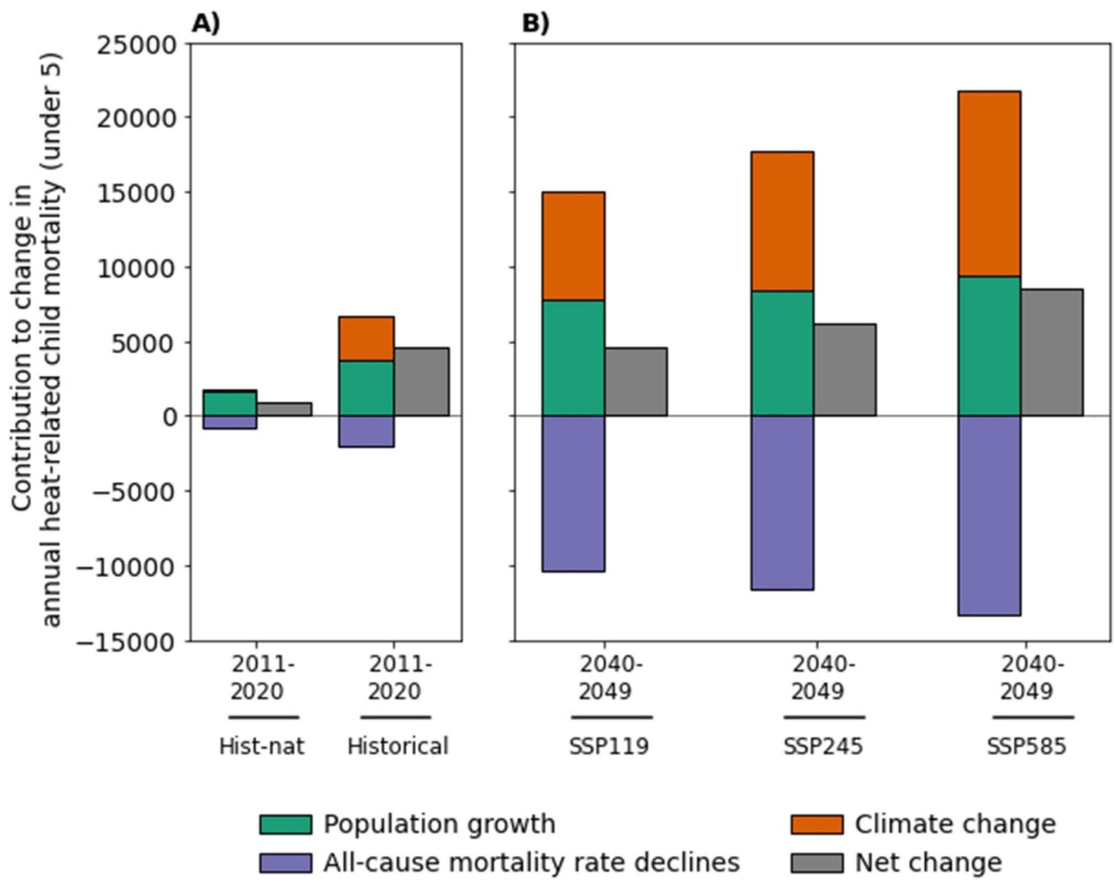

Figure 3. Contribution of changes in population, declining all-cause mortality rates, and climate change to changes in annual average heat-related child mortality. Net change in annual heat-related child deaths is in grey. 1995–2004 was the base period for calculating change. Panel (A) historical (with climate change) and hist-nat (without climate change) scenarios. Panel (B) climate change scenarios, SSP119, 245 and 585 (compared to historical scenario). Based on lower sensitivity to heat (coefficient = 0.61).

to 1995–2004. Population growth begins to slow after the 2020s, and in some countries begins to decline by the 2040s (figure S4) relative to 2019. Therefore, the net change in heat-related child mortality is high in the historical scenario (figure 3, panel (A)) compared to the climate change scenarios (figure 3, panel (B)).

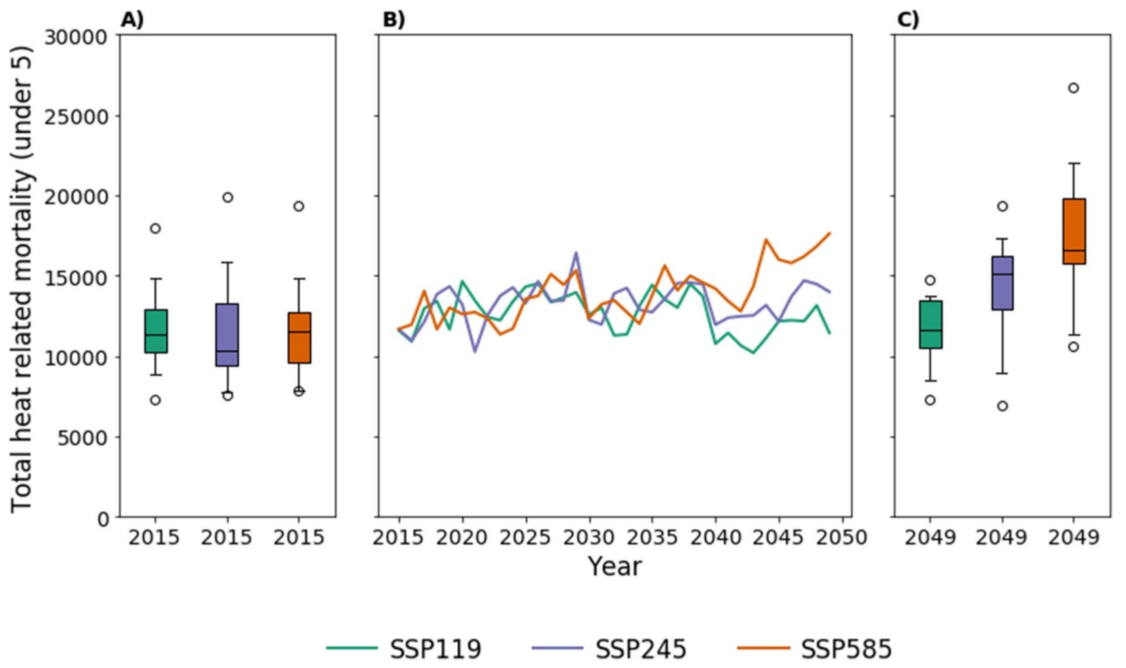

Figure 4. Projected annual heat-related child mortality in Africa with climate change. Population growth (SSP2 population scenario) and declining all-cause mortality rates (GBD reference scenario) were assumed, assuming lower sensitivity to heat (coefficient = 0.61). Panel (A) box and whisker plot for 2015. Panel (B) ensemble mean child mortality from 2015–2049. Panel (C) box and whisker plot for 2049. For panels (A) and (C), the box shows 25th–75th percentile. Box lines shows median. Whiskers show 5th–95th percentile from CMIP6 ensemble, circles show values beyond this range. Only CMIP6 models with data for all three scenarios were included. When all CMIP6 models were included, 5th–95th percentile range is larger.

3.3. Projected heat-related child mortality with climate change

Figure 4 shows that heat-related child mortality in Africa is projected to increase over the next 30 years as temperatures rise for all scenarios except SSP119. In the 2040s, for the SSP119 scenario, heat-related child mortality begins to stabilize as temperatures stabilize and health care and socio-economic factors improve, as represented by declining all-cause mortality rates (figures 3 and 4). Under SSP245 and SSP585, total heat-related child mortality continues to rise as temperatures continue to rise. When comparing these scenarios with the latest decade from the historical scenario (2005–2014), by the 2030s, annual average total heat-related child mortality in Africa increases by approximately 48% under SSP119, 53% under SSP245, and 55% under SSP585. By the 2040s, this increase is projected to be 31% for SSP119, 49% for SSP245, and 75% for SSP585. By 2049, under SSP585, annual heat-related child mortality in Africa is projected to double the annual average from 2005 to 2014. See figure S5 for results as a rate rather than total; this shows that even when removing population increase by considering mortality as a rate, large increases in deaths are projected with climate change from the 2040s onwards.

Figure 4 shows the benefits of heat deaths avoided by reducing carbon emissions. By the 2030s, following the SSP119 scenario would mean on average approximately 600–1000 children could be saved per year in Africa compared to SSP585, depending on sensitivity to heat, while SSP245 would mean on average approx. 200–300 lives saved compared to SSP585. In the 2040s, on average approx. 4000–6000 lives could be saved annually by following SSP119 compared to SSP585, and approx. 2000–3000 by following SSP245 compared to SSP585. There is a large spread in the projected temperature increases under SSP585 by mid-century (figures 4 and 5). Based on the 5th–95th percentile range from the CMIP6 ensemble, child mortality could reach over 23 000 deaths per year with low sensitivity to heat and 38 000 with high sensitivity to heat in 2049 under SSP585. If reality turned out to be closer to the upper estimates, the benefits to following SSP119 would be greater.

3.4. Heat-related child mortality beyond 2050

We did not project heat-related child mortality beyond 2050 because of uncertainties in the socio-economic projections. Impacts in the next few decades are more relevant for public health and planning horizons. In addition, there is relatively little divergence in projected temperature from the different emissions scenarios until after 2040, and so temperature increases to mid-century need to be planned for regardless.

As the century progresses, under SSP585 and SSP245, most days in the year would be above the temperature mortality threshold (figure 5). African populations would be experiencing an entirely new climate. Already by 2050, many tropical locations are expected to experience climates not currently

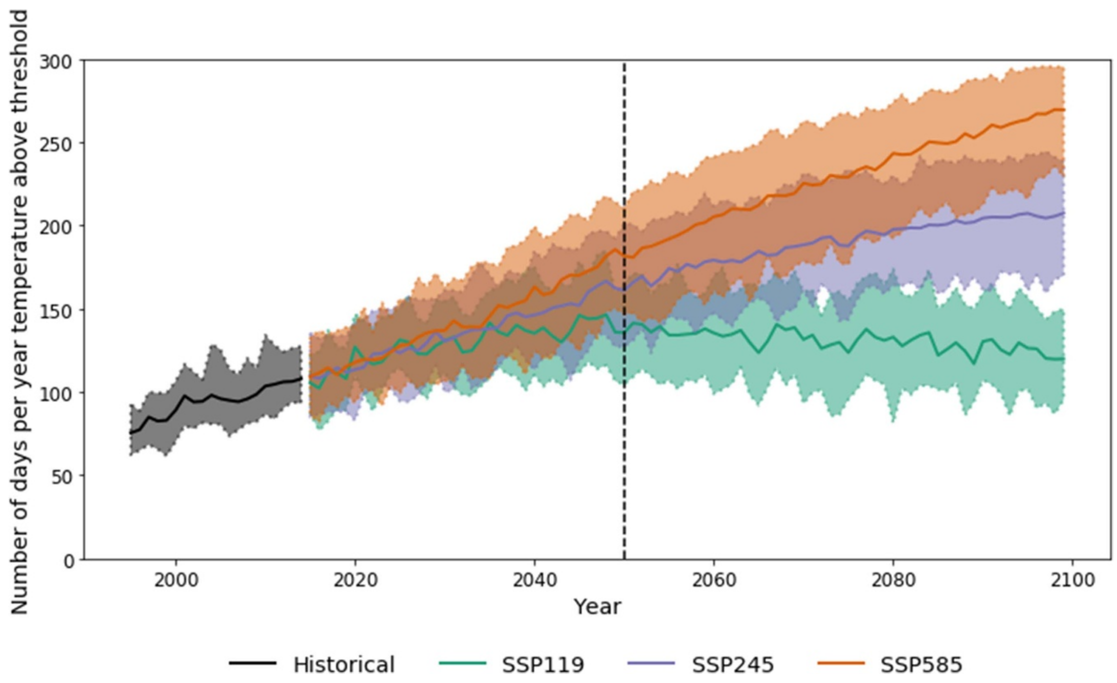

Figure 5. Number of days per year above the 1995–2010 75th percentile threshold of daily average temperature, calculated from CMIP6 climate models. Shading shows model range (5th–95th percentile from CMIP6 ensemble). Vertical line at 2050. Only CMIP6 models with data for all three climate scenarios included.

experienced anywhere on earth (Bastin *et al* 2019). Under these circumstances present-day temperature-mortality relationships are likely to be a significant underestimate of the true effects (Rocklöv and Ebi 2012). Uncertainties in the population and mortality projections (discussed below section 4), also make projecting beyond 2050 challenging.

4. Discussion

Our results show that climate change is already having a substantial impact on child mortality in Africa. Target 4.a of the Millennium Development Goals was to reduce mortality in under-5s by two-thirds between 1990 and 2015 (World Health Organization 2005). While significant reductions in under-5 mortality have been achieved since 1990, the target of the Millennium Development Goals was not met (United Nations 2015). Heat-related mortality from climate change may have undermined gains made in improved child health. The Sustainable Development Goals (SDG) have the goal of reducing under-5 mortality by 2030 (United Nations 2020). Our results suggest that if climate change is not kept to 1.5 °C of warming, rising temperatures would make meeting the SDG target increasingly difficult.

The limitations of this study include the reliance on heat-mortality relationships from existing literature that allowed the use of only two regions. Population-specific temperature mortality relationship have been found to vary by latitude, altitude, socio-economic factors such as income inequality, and factors relating to the build environment, such as prevalence of air-conditioning use (Liu *et al* 2021). It is likely that heat-mortality relationships in children to vary across populations in Africa. However, there are only a very small number of other studies on heat-mortality relationships for children in Africa. Due to different methods used, we were unable to combine information from these studies. The benefit of the effect estimates we used for our heat-mortality relationships is the use of a consistent, widely accepted method that makes comparisons more robust and the presentation of results as a range more meaningful. We acknowledge that there is undoubtedly variability in heat vulnerability across Africa due to additional factors we could not model due to a lack of epidemiologic evidence. Furthermore, the heat-mortality relationship may change over time. Therefore we have more confidence in the results from the historical period than the future period. The studies we used from Ghana and Kenya found a 0.61% and 1% increase in mortality for each 1 °C rise in temperature above the threshold temperature, respectively. A review of studies found the heat mortality impact is usually between 1% and 3% (Hajat and Kosatky 2010); however, these results are not for children, and only one of these studies was for Africa. If studies on children in Africa report a stronger heat-mortality relationship, then the heat-related child mortality would be higher than estimated here. This, however, would not change the qualitative impact of climate change on mortality, i.e. that there will be greater heat-related child mortality with SSP585 than SSP119, and mitigation will save lives.

More research and data, based on comparable methods, are needed to quantify mortality and morbidity outcomes related to heat in low-income settings, and to allow for robust estimation of exposure effects in high-risk groups such as children. Because the data required to estimate temperature-mortality relationships may not be routinely collected in many low-income countries, research should focus on other ways of understanding heat impacts in the absence of local data.

We did not assess cold-related mortality due to the limited available information in this region. The cold effect was not statistically significant in the Kenya study and in Ghana was over 12 times smaller than the heat effect. Cold effects occur at longer lag structures and there are some doubts regarding a causal association in some settings (Arbuthnott *et al* 2018). We found no robust estimates for heat effects on very young children, such as newborns (<1 month), or infants (1 year), despite these groups being especially vulnerable to heat and cold (Xu *et al* 2012).

We modelled adaptation as the general improvements in health and not as specific changes to the temperature-mortality function (World Health Organization 2014). Adaptation is often omitted from heat-related mortality assessments of climate change due to the lack of robust estimates about the extent to which adaptation will reduce impacts (Wang *et al* 2019). Successful adaptation would lead to a reduced burden of future heat-related mortality. Adaptation options may be limited in this region due to limited economic capacity, specifically the affordability of space cooling. Emerging research in African settings has identified some low costs interventions, including cool roofs, and behaviour change interventions for reducing occupational heat risks (Spencer *et al* 2022). This study supports the need for increased prevention of heat-related risks in Africa, including the adoption of public health measures such as heat health action plans. More research is needed on effective measures to reduce heat risk, including behavioural responses that can easily be adopted in low-resource settings (Rocklöv and Ebi 2012).

A further cause of uncertainty is with the all-cause mortality rate projections (Foreman *et al* 2018) that decline approximately 50% by 2040 (figure S2), based on assumptions regarding improvements in life expectancy (United Nations 2019), socio-economic factors, and health-care (Foreman *et al* 2018). Projections that assume a decline in all-cause mortality by the end of the century may not be consistent with a future world under a high-emission climate change scenario. High temperatures affect the incidence of diseases, such as malaria (Yé *et al* 2007, Chirombo *et al* 2020), diarrhoea (Smith *et al* 2014), and gastrointestinal and respiratory infections (Phung *et al* 2015, Kim *et al* 2016). These are important causes of mortality and morbidity in children under age 5 (World Health Organization 2005, 2018). Premature birth, which is in the top three causes of child death in Africa and the leading cause worldwide (World Health Organization 2018), has been shown to increase with exposure to high temperatures during pregnancy (Chersich *et al* 2020). In addition, climate change is expected to increase extreme events, and in many areas will make accessing clean drinking water more difficult (Smith *et al* 2014). It is conceivable therefore, that if temperatures continue to rise, deaths from these causes will also rise (Sheffield and Landrigan 2011). If this is the case, calculations of heat-related child mortality based on assumptions of declining total mortality would be underestimate future heat mortality.

Substantial benefits to health can be achieved by reducing carbon emissions. Even without projecting child mortality out to 2100, it is clear from figure 5 and the preceding analyses that by 2100, substantial health benefits would be achieved by following the SSP119 emissions pathway. The current global emissions trajectory tracks the high-end of the emissions scenarios (Friedlingstein *et al* 2014, Schwalm *et al* 2020). Rapid and effective mitigation and emissions reductions would entail significant reductions in heat-related mortality by the 2040s. The contrast between child mortality in SSP585 and SSP119 by the end of the century would be larger.

5. Conclusion

Our results show that climate change, through increasing exposure to high temperatures, may have already led to double the heat related child mortality compared to what would have been expected without climate change. This underscores the need for more ambitious mitigation measures to protect vulnerable populations and the need for proactive and effective adaptation. In the absence of ambitious emissions reductions targets and the introduction of adaptation measures, heat stress impacts on child mortality will increase, and under a high emissions scenario may double in Africa by 2049. Studies in other regions with tropical and sub-tropical climates have shown an impact of high temperatures on child mortality (Xu *et al* 2012, Son *et al* 2017), therefore climate change is likely to have impacted heat-related child mortality burdens in other parts of the world, particularly south Asia and South America (Romanello *et al* 2021). Our understanding of heat impacts on children, and how heat-mortality relationships could change with large amounts of warming, is limited due to the lack of physiological and epidemiological studies on heat stress in children, particularly in low-resource settings. More research is urgently needed to understand how some of the most vulnerable members of our population may be impacted by extreme heat and which health interventions would effectively reduce heat impacts. Our results highlight the urgent need for health policy to focus on heat-related child mortality, as our results show it is a serious present-day issue, which will only become more pressing as the climate warms.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: www.worldpop.org/geodata/listing?id=65https://data.unicef.org/www.wittgensteincentre.org/dataexplorer(http://ghdx.healthdata.org/record/ihme-data/global-life-expectancy-all-cause-mortality-and-cause-specific-mortality-forecasts-2016-2040, https://esgf-node.llnl.gov/projects/cmip6/.

Acknowledgments

This work was supported by the Natural Environment Research Council (NERC) (Grant Numbers NE/T013613/1, NE/T01363X/1); Research Council of Norway (RCN) (Grant Number 312601); The Swedish Research Council for Health, Working Life and Welfare in collaboration with the Swedish Research Council (Forte) (Grant Number 2019-01570); and the National Science Foundation (NSF) (Grant Number ICER-2028598); coordinated through a Belmont Forum partnership. Marsham was also funded by HyCRISTAL, IMPALA and the NCAS ACREW programme.

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