Effects of ambient heat exposure on risk of all-cause mortality in children younger than 5 years in Africa: a pooled time-series analysis

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Summary

Background Reducing child mortality is a Sustainable Development Goal, and climate change constitutes numerous challenges for Africa. Previous research has shown an association between leading causes of child mortality and climate change. However, few studies have examined these effects in detail. We aimed to explore the effects of ambient heat on neonate, post-neonate, and child mortality rates.

Methods For this pooled time-series analysis, health data were obtained from the International Network for the Demographic Evaluation of Populations and Their Health (INDEPTH) Health and Demographic Surveillance System. We included data from 29 settlements from 13 countries across Africa, collected via monthly surveys from Jan 1, 1993, to Dec 31, 2016. Climate data were obtained from ERA5, collected from Jan 1, 1991, to Dec 31, 2019. We pooled these data for monthly mean daily maximum wet bulb globe temperature (WBGT) and downscaled to geolocations. Due to data heaping, we pooled our health data on a monthly temporal scale and a spatial scale into six different climate regions (ie, Sahel [ie, Burkina Faso and northern Ghana], Guinea [ie, southern Ghana, Côte d'Ivoire, and Nigeria], Senegal and The Gambia, eastern Africa [ie, Kenya, Malawi, Tanzania, Mozambique, and Uganda], South Africa, and Ethiopia). Our outcomes were neonate (ie, younger than 28 days), post-neonate (ie, aged 28 days to 1 year), and child (ie, older than 1 year and younger than 5 years) mortality. To assess the association between WBGT and monthly all-cause mortality, we used a time-series regression with a quasi-Poisson, polynomial-distributed lag model.

Findings Between Jan 1, 1993, and Dec 31, 2016, there were 44 909 deaths in children younger than 5 years across the 29 sites in the 13 African countries: 10 078 neonates, 14 141 post-neonates, and 20 690 children. We observed differences in the association of heat with neonate, post-neonate, and child mortality by study region. For example, for Ethiopia, the relative risk ratio of mortality at the 95th percentile compared with median heat exposure during the study period was 1·14 (95% CI 1·06–1·23) for neonates, 0·99 (0·90–1·07) for post-neonates, and 0·79 (0·73–0·87) for children. Across the whole year, there was a significant increase in the relative risk of increased mortality for children in eastern Africa (relative risk 1·27, 95% CI 1·19–1·36) and Senegal and The Gambia (1·11, 1·04–1·18).

Interpretation Our results show that the influence of extreme heat on mortality risk in children younger than 5 years varies by age group, region, and season. Future research should explore potentially informative ways to measure subtleties of heat stress and the factors contributing to vulnerability.

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For the **Sustainable Development Goal** see https://www.who.int/data/gho/data/themes/topics/sdg-target-3_2-newborn-and-child-mortality

Introduction

Reducing child mortality is a Sustainable Development Goal set up by the UN. However, many regions of the world are missing the target of fewer than 25 deaths per 1000 livebirths in children younger than 5 years by 2030.[1] Concerns are highest in Africa where, for example, UNICEF reported that 58% of all deaths of children younger than 5 years in 2021 occurred.[1]

Climate change constitutes numerous challenges for Africa.[2] The number of weather extremes continues to increase;[2] for example, heatwaves that currently return once in a 100-year period were predicted to occur four times a year on average by 2070 across the continent under a high-emission scenario.[3] Changing temperatures and rainfall patterns also affect livelihoods across the continent and influence the migration of traditional nomadic groups.[4,5]

Previous research has shown a significant association between leading causes of child mortality and climate change, such as malaria and child wasting and stunting.[6,7] Heat-related child mortality was estimated to double by 2050 under a high-emission scenario in Africa.[8] For example, exposure to daily daytime mean temperatures higher than 35°C was associated with an increased likelihood of stunted growth.[9] Extreme heat is a substantial risk factor that deserves attention when attempting to reduce neonate (ie, younger than 28 days), post-neonate (ie, aged 28 days to 1 year), and child (ie, older than 1 year and younger than 5 years) mortality rates.[10]

Research in context

Evidence before this study

We conducted a scoping review in Google Scholar of the leading causes of neonate (ie, younger than 28 days) and child (ie, younger than 5 years if possible, but up to age 14 years) mortality for each site in the Health and Demographic Surveillance System for Africa of the International Network for the Demographic Evaluation of Populations and Their Health using the search terms "cause of mortality", "child mortality", "neonatal mortality", "Nanoro", "Nouna", "Ouagadougou", "Taabo", "Gilgel Gibe", "Kilite Awlaelo", "Kersa", "Harar", "Dabat", "Arba Minch", "Navrongo", "Kintampo", "Dodowa", "Farafenni", "Nairobi", "Kombewa", "Karonga", "Chokwe", "Nahuche", "Bandafassi", "Mlomp", "Niakhar", "Ifakara", "Rufiji", "Magu", "Iganga/Mayuge", "Agincourt", "Dikgale", and "Africa Centre" to identify papers published in French or English between Jan 1, 1990, and Dec 31, 2023, which returned 42 papers. The leading causes of death for children aged 1–5 years were malaria and malnutrition, both of which have been indirectly associated with climate change and heat exposure. In comparison, the leading causes of death for neonates were birth asphyxia and sepsis; however, few studies were available. We also conducted a systematic review of the literature on the Wet Bulb Globe Temperature heat metric for humans by searching Scopus between Jan 1, 1957, and July 31, 2023, using the search term "Wet Bulb Globe Temperature". Only research on humans and papers published in English were included. This search returned 913 papers. Very few studies were for neonates, with more studies on children's health during physical education in middle-income and high-income countries.

Added value of this study

We addressed a large gap in the evidence about the effects of heat exposure on child mortality in a geographical region that is predicted to be severely affected by extreme heat due to climate change. There is also little research on these effects in children younger than 5 years. Our analysis suggests that climate change might be a threat to progress in Sustainable Development Goal 3.2 in some African countries.

Implications of all the available evidence

Our findings imply that studies that do not consider different seasons and climate regions might miss nuances in heat-exposure responses. Moreover, future studies should explore the interactions between extreme heat exposure and the health, demographic, and socioeconomic factors that can contribute to heat vulnerability in the specific region. This type of research is particularly needed in Africa, where rising temperatures and little capacity for adaptation could be a major public health threat during the coming decade.

For **INDEPTH** see https://www.indepth-network.org/

The International Network for the Demographic Evaluation of Populations and Their Health (INDEPTH) Health and Demographic Surveillance System (HDSS) includes 47 settlements in 19 countries in Africa, is a way to highlight child and neonate mortality, and links to socioeconomic factors and causal vulnerabilities. For example, multiple sites from the HDSS show evidence of the effects of distance from health-care facilities or water sources on mortality outcomes for people who are permanent residents in those sites.[11–13] Moreover, there was a negative association between exposure to extreme heat and stillbirth and preterm birth in 14 lower-middle-income countries, including parts of Africa, via data from the Demographic Health Surveys programme.[14] However, to date, no cross-country study has been conducted on heat exposure and neonate, post-neonate, and child mortality across Africa.

In most epidemiological studies, there is no consideration of change in the relative risk response curve during different seasons or among different climate zones with seasonal adjustments,[14,15] which differs from existing climate studies on heat exposure and heatwaves. For example, the monthly moving average approach is sometimes used as a threshold to indicate extreme heat.[16–18]

We aimed to explore the effects of heat stress, as indicated by the international standard metric of wet bulb globe temperature (WBGT), on neonate, post-neonate, and child mortality rates from HDSS data for 29 sites across 13 countries in Africa. We aimed to explore the effects of heat exposure on all-cause neonate, post-neonate, and child mortality rates in different seasons and climatic regions, and to highlight the relationship between heat exposure and neonate, post-neonate, and child mortality rates.

Methods

Study design and health data

For this pooled time-series analysis, health data were obtained from the INDEPTH HDSS.[19] We included data from 29 settlements from 13 countries across Africa (ie, The Gambia, Senegal, Ghana, Burkina Faso, Nigeria, Côte d'Ivoire, Ethiopia, Kenya, Tanzania, Uganda, Malawi, Mozambique, and South Africa), collected via monthly surveys from Jan 1, 1993, to Dec 31, 2016. Data ranged from subnational (ie, a collection of villages) to a single settlement (ie, one village)[20] and were consolidated all-cause mortality data.

Ages of neonates, post-neonates, and children were defined via recorded dates of birth and death in the HDSS datasets, provided by monthly vocal autopsies. We did not consider babies on day 0, to avoid the inclusion of stillbirths. HDSS was chosen as it took vocal autopsies at very regular intervals. To assess the quality of data, we visualised the data from all the sites and considered the timeframe covered by each site.

Ethics approval was provided by the University of Graz.

Climate data

Climate data were obtained from ERA5. Data were collected from Jan 1, 1991, to Dec 31, 2020. Data were WBGT.

ERA5 was chosen as the data source as the necessary observations were not available near all sites. Furthermore, it is a state-of-the-art dataset (eg, observations modelled into a gridded dataset).

Records were affected by data heaping (ie, exact dates not known and so recorded as the same date). For our analysis, this date was the 15th of each month (appendix p 3).[15] Due to data heaping, we pooled our health data on a monthly temporal scale and a spatial scale, on the basis of literature on the migration of monsoons and temperature trends, into six different climate regions (ie, Sahel [ie, Burkina Faso and northern Ghana], Guinea [ie, southern Ghana, Côte d'Ivoire, and Nigeria], Senegal and The Gambia, eastern Africa [ie, Kenya, Malawi, Tanzania, Mozambique, and Uganda], South Africa, and Ethiopia).[3,16,21–23]

Across western Africa, the climate is a meridional large-scale temperature gradient between the northern and southern areas, partly influenced by the sea-surface temperature in the equatorial Atlantic. This gradient is crucial in the development and northward displacement of the west African monsoon during spring and summer.[16] Furthermore, Senegal and The Gambia have a different pattern of heatwave development compared with other areas in the region.[16] In the Sahel region, local factors such as Harmattan wind anomalies and changes in circulation influence heatwaves, and different seasons have specific atmospheric anomalies.[22] These differences in climate show the need for three different climate regions in west Africa in this analysis: the Guinea coast (Guinea), the Sahel region (Sahel), and Senegal and The Gambia.

Eastern Africa is one region, and there is less evidence of heatwaves in this region than in west Africa. However, under an RCP8·5 high-emission scenario (ie, greenhouse gas emissions continue to increase unmitigated), the Great Lakes Region—referred to in our analysis as eastern Africa—is likely to have a substantial increase in heat stress by the end of the 21st century.[23] This finding showed that considering spatial heterogeneity in climate estimates and implementing high-resolution models are important for accurate regional risk assessments, highlighting the need to consider different climate regions.[23] Ethiopia and South Africa are in different regions and therefore again have slightly different drivers of heatwaves and patterns of temperature change, resulting in our final two climate regions.[3,21]

We used extreme heat as a general term that included heat stress, heatwaves, and hot weather. Heat stress is defined as "a build-up of body heat as a result of exertion and/or external environment".[24] We used the international standard heat metric of WBGT for heat exposure.[25] WBGT is calculated for the up-to-date dataset ERA5, which provides global gridded data every 1 h at a 0·25×0·25° grid scale, including for data-sparse regions such as African countries.[26,27] We pooled these data for monthly mean daily maximum WBGT and downscaled to geolocations, defined by the longitude and latitude of the centre of HDSS sites via a nearest-neighbour interpolation method, to be able to provide information on heat exposure at the local level to the same aggregated scale as the health data.[28]

For **ERA5** see https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5

Outcomes

Our outcomes were neonate (ie, younger than 28 days), post-neonate (ie, aged 28 days to 1 year), and child (ie, older than 1 year and younger than 5 years) mortality.

See Online for appendix

Statistical analysis

First, we conducted an Augmented Dickey–Fuller test of time-series stationarity on the relationship between

	Child mortality rate	Post-neonate mortality rate	Neonate mortality rate	Daily maximum WBGT
Sahel (Burkina Faso and northern Ghana)				
All seasons*	3·5 (0·4–19·7)	2·1 (0·3–10·3)	1·6 (0·5–5·5)	28·3°C (23·4–30·6)
Dry season	3·1 (0·6–9·0)	1·9 (0·2–6·3)	1·6 (0·3–4·7)	28·2°C (23·7–30·6)
Monsoon season	4·0 (0·4–19·7)	2·4 (0·3–10·3)	1·6 (0·3–5·5)	27·5°C (25·5–29·3)
Guinea (southern Ghana, Côte d'Ivoire, and Nigeria)				
All seasons*	5·5 (0·4–34·6)	3·4 (0·3–16·3)	1·9 (0·3–7·7)	27·3°C (19·3–31·6)
Dry season	5·5 (0·4–20·4)	3·4 (0·4–13·1)	1·9 (0·4–7·7)	25·6°C (19·3–31·1)
Monsoon season	5·5 (0·4–34·6)	3·5 (0·3–16·3)	1·9 (0·3–7·5)	29·0°C (26·6–31·6)
Senegal and The Gambia				
All seasons*	9·2 (0·6–59·6)	4·9 (0·5–28·1)	3·7 (0·5–20·5)	27·6°C (19·2–31·1)
Dry season	8·5 (0·6–59·6)	4·6 (0·5–28·1)	3·5 (0·5–20·0)	26·7°C (19·2–31·1)
Monsoon season	10·3 (0·8–46·7)	5·3 (0·5–26·2)	4·1 (0·5–20·5)	29·1°C (27·1–30·5)
Eastern Africa (Kenya, Malawi, Tanzania, Mozambique, and Uganda)				
All seasons*	7·7 (0·6–37·3)	3·5 (0·3–37·3)	2·4 (0·3–13·1)	23·5°C (17·2–29·2)
Dry and hot season	4·6 (0·6–37·3)	4·0 (0·4–37·3)	2·4 (0·4–10·7)	24·9°C (20·0–29·1)
Monsoon season 1	4·6 (0·7–15·8)	3·7 (0·3–15·8)	2·5 (0·4–10·7)	24·1°C (19·2–29·3)
Dry and cold season	4·2 (0·5–32·1)	3·4 (0·4–19·6)	2·4 (0·3– 13·1)	22·0°C (17·2–27·0)
Monsoon season 2	6·8 (0·6–15)	3·1 (0·5–10·9)	2·5 (0·5–6·5)	24·5°C (19·9–28·9)
Ethiopia				
All seasons*	3·9 (0·3–24·3)	2·7 (0·4–11·8)	2·9 (0·5–13·2)	21·3°C (16·5–23·9)
Dry season	3·7 (0·5–18·1)	2·6 (0·42–11·5)	3·0 (0·45–13·2)	21·3°C (16·5–24·0)
Wet season	4·2 (0·2–24·3)	4·6 (0·40–11·8)	2·9 (0·52–10·3)	21·1°C (18·1–23·5)
South Africa				
All seasons*	4·1 (0·4–11·7)	3·0 (0·3–12·1)	1·3 (0·3–10)	22·5°C (16·3–27·2)
Summer	2·4 (0·5–7·9)	2·7 (0·5–8·6)	1·2 (0·4–3·7)	25·4°C (23·4–27·2)
Autumn	4·5 (0·5–8·6)	3·0 (0·4–9·6)	1·3 (0·5–10)	19·2°C (19·4–26·1)
Spring	2·5 (0·5–11·7)	2·6 (0·5–7·9)	1·4 (0·5–4·4)	22·5°C (20·1–25·4)
Winter	5·0 (0·4–10·7)	2·9 (0·3–12·1)	1·3 (0·3–6·0)	23·2°C (16·3–21·5)

Data are deaths per 1000 livebirths (95% CI). WBGT=wet bulb globe temperature. *Annual mean deaths per 1000 livebirths during all seasons in the entire study period.

Table: **Descriptive statistics for pooled Health and Demographic Surveillance System sites across climate regions and seasons for mean child, post-neonate, and neonate mortality rates and mean daily maximum WBGT** mortality rates and WBGT. This test showed that all the data were stationary, meaning that seasons and months did not need to be included as fixed effects in our model. To assess the association between WBGT and monthly all-cause mortality rates, we used a time-series regression with a quasi-Poisson, polynomial-distributed lag model in the dlnm package of R version 4.1.2, which has been used in previous literature.[14] We considered the instantaneous effects of lags from 0 to 3 months.

We report risk ratios for monthly all-cause mortality rates for neonates, post-neonates, and children compared with values of heat exposure, calculated via the attribution of risk as in the dlnm package. These values are reported with a 95% CI evaluating the increase from the median value of exposure for WBGT, known as the centroid, to the 95th percentile. Median value was chosen as the comparative value as it is the value to which children younger than 5 years are most exposed. We compared responses across different seasons and used different seasonal thresholds based on median WBGT exposure (appendix pp 3–10).

The INDEPTH network conducted data cleaning. Missing data were retained in the model.

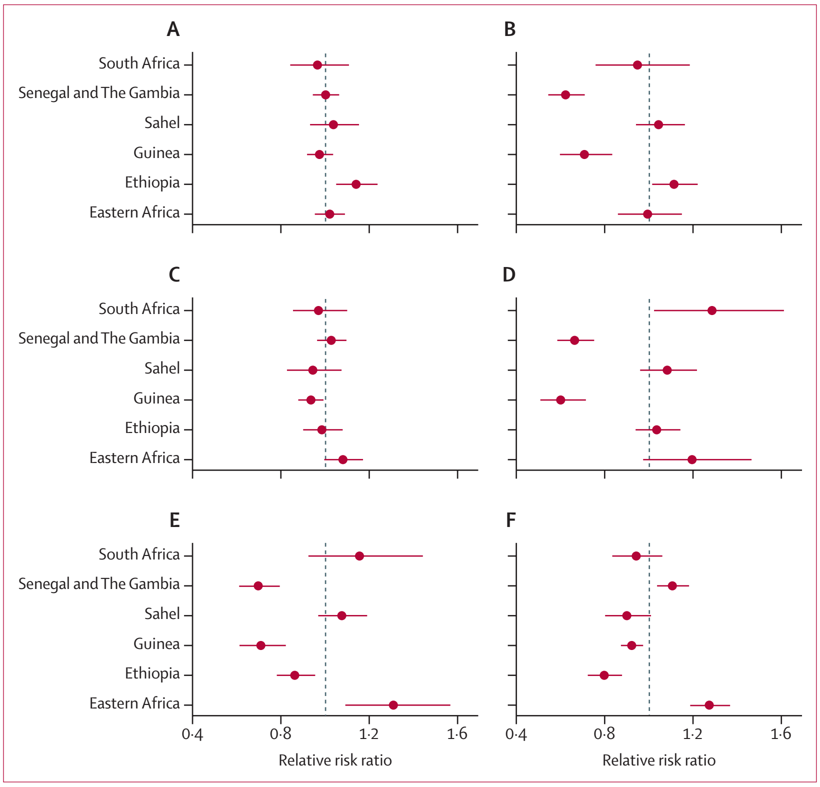

Figure 1: **Relative risk ratios for mortality during high heat exposure (ie, 95th percentile) compared with median heat exposure via Wet Bulb Globe Temperature during the whole study period**
Relative risk ratio for neonate mortality rate during the whole year (A) and the hottest season (B). Relative risk ratio for post-neonate mortality rate during the whole year (C) and the hottest season (D). Relative risk ratio for child mortality rate during the whole year (E) and the hottest season (F). Sahel region includes Burkina Faso and northern Ghana. Guinea region includes southern Ghana, Côte d'Ivoire, and Nigeria. Eastern Africa region includes Kenya, Malawi, Tanzania, Mozambique, and Uganda. Error bars show 95% CI.

Sensitivity and post-hoc analyses are described in the appendix (p 10). R version 4.1.2 was used for all analysis.

Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

Between Jan 1, 1993, and Dec 31, 2016, there were 44 909 deaths in children younger than 5 years across the 29 sites in the 13 African countries: 10 078 neonates (ie, younger than 28 days), 14 141 post-neonates (ie, aged 28 days to 1 year), and 20 690 children (ie, older than 1 year and younger than 5 years). Mean neonate mortality rate was 2·3 deaths (IQR 1·3–4·1) per 1000 livebirths, post-neonate mortality rate was 3·30 deaths (5·3–1·9) per 1000 livebirths, and child mortality rate was 5·65 deaths (9·2–2·4) per 1000 livebirths across the study period and the sites in the six regions (table).

We observed differences in the association of heat with neonate, post-neonate, and child mortality rates in different regions. For Ethiopia for the whole year, the relative risk ratio at the 95th percentile compared with median heat exposure was 1·14 (95% CI 1·06–1·23) for neonates, 0·99 (0·90–1·07) for post-neonates, and 0·79 (0·73–0·87) for children. For eastern Africa for the whole year, the relative risk ratio was 1·02 (0·96–1·08) for neonates, 1·06 (1·00–1·17) for post-neonates, and 1·27 (1·19–1·36) for children. For South Africa for the whole year, the relative risk ratio was 0·97 (0·84–1·10) for neonates, 0·97 (0·86–1·10) for post-neonates, and 0·94 (0·84–1·06) for children. For Sahel for the whole year, the relative risk ratio was 1·04 (0·94–1·15) for neonates, 0·94 (0·83–1·07) for post-neonates, and 0·90 (0·81–1·01) for children. For Guinea for the whole year, the relative risk ratio was 0·98 (0·92–1·03) for neonates, 0·94 (0·89–0·99) for post-neonates, and 0·92 (0·88–0·97) for children. Finally, for Senegal and The Gambia for the whole year, the relative risk ratio was 1·00 (0·95–1·06) for neonates, 1·03 (0·97–1·09) for post-neonates, and 1·11 (1·04–1·18) for children (figure 1).

Across the whole year, there was a significant increase in the relative risk of increased mortality for children in eastern Africa (relative risk 1·27, 95% CI 1·19–1·36) and Senegal and The Gambia (1·11, 1·04–1·18; figure 2C, F). However, when considering the hottest season only (table), there was a significant increase in this relative risk for South Africa, eastern Africa, and Sahel (figure 2G, I, J; appendix pp 4–9).

The two leading causes of death in post-neonates and children across the 29 sites were malaria and HIV infection and the leading cause of death in neonates was birth asphyxia, although there were multiple sites in which the leading cause of death was missing (appendix pp 10–11). In sensitivity analyses showing the relative risk response by season in each region and the relative risk ratio by leading

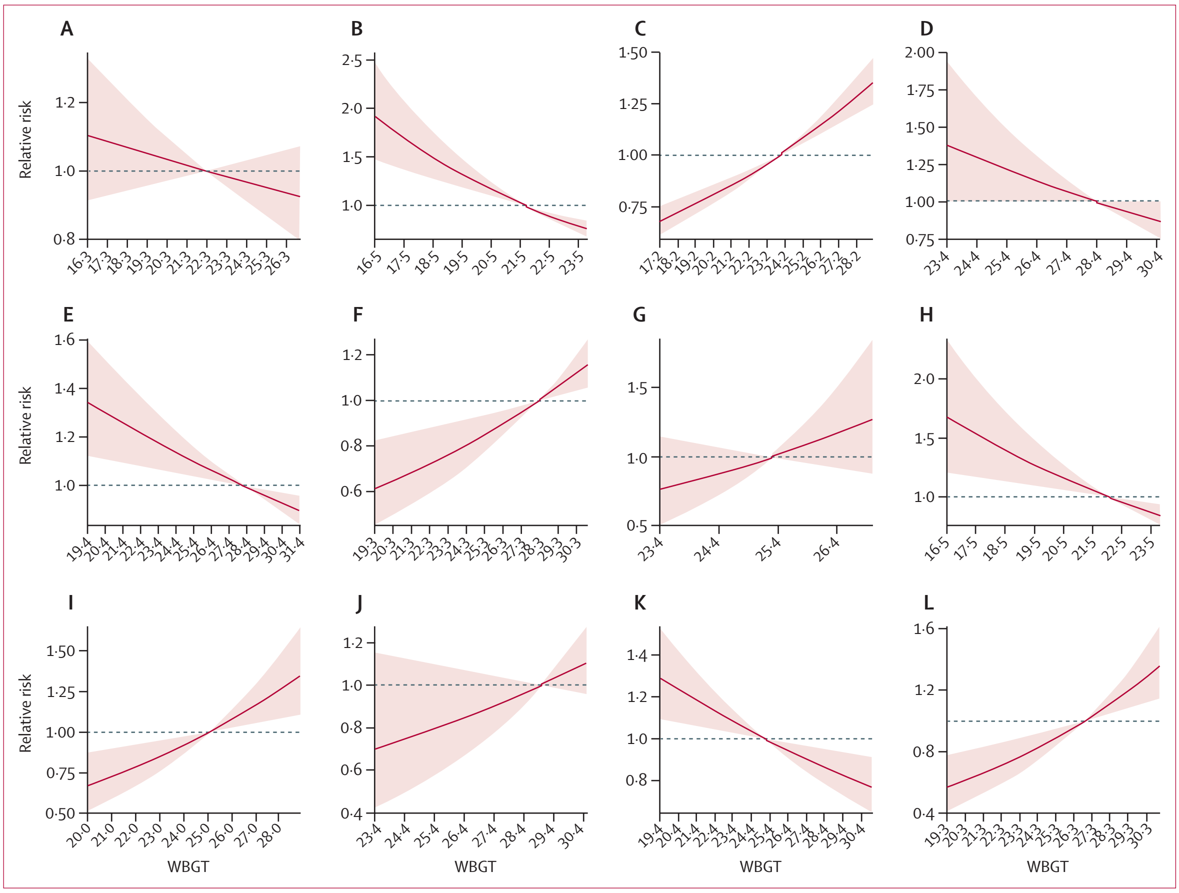

Figure 2: **Relative risk response curve of child mortality rate compared with WBGT**
During the whole year for South Africa (A), Ethiopia (B), eastern Africa (C), Sahel (D), Guinea (E), and Senegal and The Gambia (F). During the season in which the monthly mean daily maximum WBGT is at its highest for South Africa (G), Ethiopia (H), eastern Africa (I), Sahel (J), Guinea (K), and Senegal and The Gambia (L). Eastern Africa region includes Kenya, Malawi, Tanzania, Mozambique, and Uganda. Sahel region includes Burkina Faso and northern Ghana. Guinea region includes southern Ghana, Côte d'Ivoire, and Nigeria. Median is the centroid. Error bars show 95% CI. Please note that scales of graphs are different. WBGT=wet bulb globe temperature.

cause of death in each region, there was overall no change in risk outcomes from the main results (appendix p 11).

Discussion

We found differences in the relative risk response curves for climate regions and seasons regarding heat exposure. Our results show that the response of the relative risk of increased mortality compared with WBGT values can change on the basis of season and time evaluated. Furthermore, we found differences between neonate, post-neonate, and child mortality rate responses to heat exposure, which could be explained by differences in the leading causes of death.[11–13] The leading cause of death at most sites was different for children and post-neonates compared with neonates. Our results show that pooling health outcomes, such as all-cause mortality during multiple seasons and climate zones, could be misleading about nuances in response to heat exposure.

A seasonal effect similar to that found in our analysis was shown in an analysis of data from Burkina Faso, with higher child mortality during the wet season than during the dry season, attributed to increased malaria prevalence.[12] Furthermore, demographic factors such as age, sex, maternal education, ethnicity, and multiple births were significantly associated with variations in child mortality, which were not considered in this analysis.[12] The analysis also suggested that improving access to inpatient health-care facilities and maternal education could reduce child mortality rates.[12]

Our seasonal differences are supported by another study that also found distinct seasonal patterns of malaria and meningitis spread, with increased transmission rates in southern Nigeria due to temperature, aerosol (dust), and precipitation distributions.[29] Meningitis prevalence was strongly correlated with aerosols and temperature in specific zones, whereas rainfall was correlated with malaria prevalence.[29] This study highlights the necessity of understanding climatic factors in disease management in a changing climate environment.[29]

A 2010 study used WBGT to map thermal changes for children younger than 5 years in the neonatal clinical intensive unit at University of Washington Medical Center

(Washington State University, Seattle, WA, USA) and found statistically significant differences in season and room, as well as interactions between season and room.[30] Humidity was also shown to be a significant seasonal factor, compared with ambient room temperature.[30]

Our results and those of others show that age, season, and climate regions have different heat thresholds. WBGT is primarily used in occupational settings, where there are rest–work guidelines across age, sex, and climate region. We suggest that it is essential that international standards organisations develop thresholds that reflect characteristics that work for the entire population. Furthermore, WBGT is considered the most robust heat metric in physiology studies and has been previously used in studies of children and neonates.[30,31]

For the **Expanded Programme on Immunization** see https://www.who.int/teams/immunization-vaccines-and-biologicals/essential-programme-on-immunization

The two leading causes of death in post-neonates and children were malaria and HIV infection. Malaria is a vector-borne disease that is associated with climate change.[6,32,33] For example, a longitudinal study of one of the sites in Burkina Faso that was also included in this analysis explored all-cause mortality, cause-specific mortality, and the relationship between temperature and precipitation, with a focus on malaria.[34] There is less evidence of an association between HIV and heat exposure; HIV might deplete a child's immune system and make them more likely to die during periods of high heat than children without HIV.[32]

The leading cause of death reported in neonates was birth asphyxia. There is little evidence of an association between heat and birth asphyxia but, theoretically, heat stress affects the production of cortisol, which could affect biological pathways that reduce oxygen to the fetus.[35] A study in northwest Ethiopia, one of the regions included in our analysis, investigated factors contributing to delays in care seeking associated with neonate deaths.[11] Delays at home and in health-care facilities were primary contributors to neonate deaths, with birth asphyxia being the leading cause, indicating the importance of targeted interventions to reduce delays in care seeking and emphasising the need to improve the quality of care and education.[11] Research on quality of care and physiological pathways that lead to birth asphyxia as a cause of death should be a priority.

We suggest that future studies explore, in more detail, specific leading causes of mortality between gaps for different causes and the association with extreme heat via clinical methods developed to assess exposure to extreme heat. For example, a study from The Gambia involved considerations of heat stress, maternal age, gestational month, nutritional status, and other factors to predict fetal distress.[36] Furthermore, heat-stress indices should be validated and fetal changes in heart rate and biomarkers related to heat strain or fetoplacental function should be explored[36] to establish the physiological pathways influenced by heat.

We suggest that implementing prevention strategies for seasonally leading causes of death could also reduce the effects of extreme heat exposure. For example, the co-development of an early-warning system for meningitis and the creation of a vaccination programme, which was financed and implemented before the season of occurrence in the Sahel region.[29] In Senegal, mortality in children younger than 5 years decreased three-fold between the 1970s and the 2000s, with a notable acceleration in decline linked to the Expanded Programme on Immunization in 1987.[37] Vaccination efforts have substantially reduced deaths from infectious diseases, particularly measles.[37]

There are some limitations of our analysis to consider (eg, the pooled time-series regression method). A case-crossover design, in the absence of data heaping, would have allowed for a daily temporal scale of heat exposure. Moreover, health and climate data were matched with the central geolocation point of settlements rather than individual addresses, meaning there could have been slight differences with actual heat exposure. There were also limitations due to designating age categories of neonates, post-neonates, and children, with overlaps between groups because of the reporting methods of the health dataset. Finally, the HDSS used no socioeconomic variables, which would be advantageous to explore in future research.

Our results show that there are differences in the risk of mortality in children younger than 5 years via WBGT as an indicator of extreme heat for region, season, and age. We suggest that future research focuses on further development in knowledge of mortality in children younger than 5 years and climate change, including aspects of social vulnerability. Furthermore, we suggest that interventions for leading causes of death could be protective for heat exposure. However, we note that any adaptation options to heat do not negate the need to reduce greenhouse gases to net zero to stop further increases in exposure to heat extremes.

Contributors
CB conceptualised the analysis, designed the methodology, did the formal analysis, was an investigator, acquired resources, wrote the original draft of the manuscript, and reviewed and edited the manuscript. KW designed the methodology, visualised the data, and reviewed and edited the manuscript. TM curated the data and reviewed and edited the manuscript. KW, TM, and IMO accessed and verified the data. DJ conceptualised the analysis, designed the methodology, acquired resources, and reviewed and edited the manuscript. JDB acquired resources and reviewed and edited the manuscript. MFC acquired resources and funding and edited the manuscript. IMO conceptualised the analysis, designed the methodology, acquired resources and funding, reviewed and edited the manuscript, and was a supervisor.

Declaration of interests
DJ is funded by the Takeda Foundation. All other authors declare no competing interests.

Data sharing
Health data are available at https://www.indepth-ishare.org/index.php/catalog/Consolidated_HDSS_data. Climate data are available at https://zenodo.org/records/8021197. The data-analysis protocol for the Heat Indicators for Global Health (HIGH) Horizons project, which includes this pooled time-series analysis, is available at https://doi.org/10.5281/zenodo.10947995. Software code is available on request from the corresponding author.

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