# Estimating the burden of temperature-related low birthweight attributable to anthropogenic climate change in low-income and middle-income countries: a retrospective, multicentre, epidemiological study

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## Summary

**Background** Pregnant individuals are particularly susceptible to non-optimal temperatures due to their physiological status. Moreover, pregnancy is a crucial period for programming fetal health. Quantifying the impact of non-optimal temperature exposure and the contribution of anthropogenic climate change is crucial for mitigating and adapting to climate-related health risks. However, this has not been thoroughly studied in pregnant individuals in low-income and middle-income countries (LMICs).

**Methods** Using data from 511 449 births across 31 LMICs from 1990 to 2018, we linked climate simulations (with and without anthropogenic forcing) to spatiotemporally resolved temperature data and birthweight records. We assessed the association between heat and cold exposure (ie, >90th and <10th percentile of temperature by region) during pregnancy and birthweight across different regions. We then used temperature simulations from both historically forced and natural-only forced climate models to estimate changes in exposure due to anthropogenic climate change and to quantify the burden of temperature-related low birthweight (ie, a birthweight <2500 g) attributable to anthropogenic climate change.

**Findings** Heat exposure during pregnancy, compared with the optimal temperature range, was associated with an increased risk of low birthweight in several regions: southern Asia (odds ratio 1·41, 95% CI 1·34–1·48), western Africa (1·12, 1·02–1·24), and eastern Africa (1·40, 1·27–1·55). Cold exposure increased the risk of low birthweight in central Africa (1·31, 1·10–1·56), southern Africa (1·18, 1·02–1·36), and eastern Africa (1·14, 1·02–1·26). Anthropogenic climate change contributed to approximately 59·2% (95% CI 16·6–94·3), 89·0% (51·0–100·0), and 77·3% (27·0–100·0) of heat-related low birthweight cases in southern Asia, western Africa, and eastern Africa, respectively. Conversely, in regions where cold exposure was predominant, anthropogenic climate change reduced the burden of low birthweight.

**Interpretation** Our study provides quantitative estimates of the contribution of anthropogenic climate change to the low birthweight burden in LMICs. These findings can inform strategies for climate mitigation and adaptation in LMICs and help reduce global health inequalities.

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## Introduction

According to the most recent report by the Intergovernmental Panel on Climate Change, global warming dominates the long-term regional temperature changes, with greenhouse gas emissions being the primary driver of increased intensity, frequency, and duration of heat, as well as decreased intensity of cold.[1] Since the 19th century, human activities across sectors such as energy, industry, transportation, construction, agriculture, and land use have been the major sources of greenhouse gas emissions, making them the leading cause of climate change. Although no country is immune to the impacts of climate change, low-income and middle-income countries (LMICs) are the most vulnerable and heavily burdened.[2]

Pregnant individuals are particularly vulnerable to non-optimal temperatures due to their physiological status. Exposure to heat or cold during pregnancy can adversely affect fetal growth, potentially leading to a reduction in birthweight. Heat exposure can cause dehydration in pregnant individuals and damage cells, the placenta, and the vascular system, thereby affecting uterine blood flow and placental exchange necessary for fetal development.[3,4] Cold exposure narrows veins and arteries, increases cardiovascular pressure, and places additional stress on the heart, similar to the effects of

## Research in context

### Evidence before this study

Global climate change poses a major threat to human health. Although no country is immune to the health impacts of climate change, low-income and middle-income countries (LMICs) are the most vulnerable and heavily burdened. In the context of climate change, pregnant individuals are particularly vulnerable. Maternal exposure to climate risks, including non-optimal temperatures, can substantially impact offspring health. Previous epidemiological studies, primarily from high-income countries, have reported significant decreases in birthweight associated with heat or cold exposure during pregnancy. However, evidence from LMICs remains scarce, and the findings from existing studies on maternal temperature exposure and birthweight have been inconsistent. The Intergovernmental Panel on Climate Change AR6 concluded that human activities are the primary driver of global climate change. Beyond understanding the impact of heat or cold exposure on human health, identifying the contribution of anthropogenic climate change to these effects to better inform climate change response is crucial. We searched PubMed for articles published between Jan 1, 2010, and March 30, 2024, using the following search terms: ("human-induced climate change" OR "anthropogenic climate change") AND ("disease" OR "health" OR "incidence" OR "mortality" OR "birth" OR "fetal"). Articles not involving the Detection and Attribution Comparison Model Intercomparison Project or health outcomes were excluded. No language restriction was applied. Although several attribution analyses quantitatively estimated the contribution of anthropogenic climate change to mortality, only one study in China has estimated heat-related preterm births attributable to anthropogenic climate change. To the best of our knowledge, no studies have comprehensively quantified the impact of anthropogenic climate change on fetal health in LMICs to date.

### Added value of this study

This study addresses a crucial gap by focusing on multiple LMICs in southern Asia and sub-Saharan Africa. By integrating advanced climate simulations, high-resolution temperature data, and Demographic and Health Survey data, we examined the association between heat and cold exposure during pregnancy and birthweight. We also quantified the burden of temperature-related low birthweight attributable to anthropogenic climate change. Our findings underscore a robust and spatially heterogeneous association between heat and cold exposure during pregnancy and birthweight in LMICs, providing further evidence of low birthweight burden posed by anthropogenic climate change.

### Implications of all the available evidence

This study contributes to a comprehensive understanding of the impact of heat and cold exposure during pregnancy on birthweight in LMICs. The findings have major implications for global public health by identifying vulnerable areas and populations for which climate change threatens early-life health. Furthermore, by quantifying the contribution of anthropogenic climate change to heat-related and cold-related low birthweight, our study can guide the allocation of the Loss and Damage Fund to populations most affected by climate change-related health risks and inform climate mitigation and adaptation strategies in LMICs.

heat exposure.[5] Additionally, both heat and cold are associated with oxidative damage and systemic inflammation,[6,7] which can further contribute to decreased fetal growth.[8,9] In addition to these physiological challenges, pregnant individuals in LMICs often face compounded social disadvantages in the context of climate change, including little access to essential knowledge, resources, and prenatal services that are needed to effectively adapt to non-optimal temperatures.

Previous epidemiological studies, primarily from high-income countries,[10–13] have found associations between non-optimal temperature exposure during pregnancy and reduced birthweight.[14] For example, a US study of 29 million newborns found that both high and low temperatures during pregnancy were associated with low birthweights, with reductions of 15 g (95% CI –17 to –13) and 6 g (–8 to –4), respectively.[8] In 2020, an estimated 19·8 million infants were born with low birthweight (ie, a birthweight <2500 g) worldwide, with the vast majority coming from LMICs, particularly in southern Asia (44·5%) and sub-Saharan Africa (27·1%).[15,16] However, evidence on the relationship between non-optimal temperatures and birthweight in LMICs remains limited,[17–20] and findings have been inconsistent. While two studies reported a negative association between environmental temperatures during pregnancy and birthweight,[17,18] two others found a positive association.[19,20]

In recent years, the Detection and Attribution Model Intercomparison Project (DAMIP),[21] a sub-project of the Coupled Model Intercomparison Project Phase 6, has enabled researchers to quantitatively evaluate the contribution of anthropogenic climate change to health outcomes. Previous studies have conducted attribution analyses focusing primarily on mortality.[22–24] For instance, one study found that anthropogenic climate change contributed to 370 heat-related deaths in Switzerland during the summer of 2022.[22] Another study, done globally, revealed that 37·0% of warm season heat-related fatalities could be attributed to anthropogenic climate change.[24] A study in China estimated that approximately 26% of heatwave-related preterm births each year were attributed to anthropogenic climate change, resulting in substantial human capital losses estimated at more than US$1 billion.[25] Despite these advances, the impact of human-induced climate change on temperature-related birthweight remains largely unexplored, particularly in LMICs.

Therefore, we aimed to investigate the association between maternal exposure to non-optimal temperatures during pregnancy—both hot and cold—and birthweight across different regions. Additionally, we aimed to quantify the burden of low birthweight attributable to anthropogenic climate change using climate simulation data.

## Methods

### Population data

We selected all Demographic and Health Surveys (DHSs) done between 1990 and 2018 in southern Asia (three countries) and sub-Saharan Africa (28 countries; appendix pp 8–10). We obtained data from 1 839 959 women aged 15–49 years. Among these, 423 946 women had at least one birth record, with up to six recent delivery records per woman. Demographic characteristics and details of each newborn were extracted. Stillbirths (n=3598), multiple births (n=5421), and births with abnormal birthweights (ie, <500 g or >6000 g; n=491) were excluded.

GPS information on the survey units (ie, villages or residential clusters) has become available for some surveys. These clusters typically correspond to census enumeration areas, with the waypoint located at the geographical centre of the cluster or segment. GPS coordinates were collected in the field using GPS receivers with an accuracy of approximately 15 m. To ensure privacy, all geographical coordinates were randomly shifted 2–10 km. More information on GPS data collection is provided in the Data Collection Handbook.[26,27] Individuals with missing GPS or exposure information (n=6856) were further excluded, resulting in a final analysis of 511 449 infants from 407 200 mothers (appendix p 24).

### Exposure assessment

For each included birth, we estimated the gestational length using the DHS reproductive calendar, similar to previous studies.[28,29] The DHS calendar provides a record of a woman's reproductive events, including pregnancies, abortions, births, etc, for approximately 5–7 years before the survey. We extracted all available pregnancy and birth events for each woman and calculated the gestational age at a monthly level. This method allowed us to obtain gestational age for 410 274 births. For births (n=4303) from DHS surveys for which the calendar had not been applied, we assigned values based on information on preterm birth, with extremely preterm births coded as 7, preterm births as 8, and term births as 9. Unfortunately, we could not obtain the exact gestational age for the remaining 96 872 births, so we assigned 9 months for them, referring to a previous study.[27]

We obtained the monthly mean 2 m air temperature from the Climatic Research Unit gridded Time Series (version 4.05) dataset,[30] which has a horizontal resolution of 0·5°×0·5° (approximately 50 km). The monthly mean 2 m relative humidity was sourced from the latest global atmospheric reanalysis, the European Centre for Medium-range Weather Forecasts Reanalysis (version 5),[31] with a spatial resolution of 0·25°×0·25° (approximately 25 km). We bilinearly interpolated the 2 m air temperature and relative humidity data to align with the DHS geocoded residential cluster. The average temperature over the entire gestation period was considered the temperature exposure during pregnancy, with relative humidity treated similarly.

### DAMIP data

DAMIP is a sub-project of the Coupled Model Intercomparison Project Phase 6,[21] designed primarily to better estimate the contribution of anthropogenic and natural forcing changes to observed global warming and other climate variable changes at international and regional scales. To assess the contribution of human-induced climate change to temperature-related low birthweight, we applied DAMIP to construct two scenarios: a factual scenario (ie, historical climate simulations [hist] in which climate change is driven by both human activities and natural forcing) and a counterfactual scenario (ie, hist-nat climate simulations, in which climate change is driven solely by natural forcing). The temperature data from historical climate simulations is available up to 2014, so we used Shared Socioeconomic Pathway 3–7·0 simulations from 2015 to 2018 as a proxy for the historical scenario.[24] Detailed information on the six DAMIP climate models used is provided in the appendix (p 11). For this study, we required the simulated temperature to be DAMIP outputs, which have been bias-adjusted and statistically downscaled to a 0·5°×0·5° horizontal resolution. Only one simulation per climate model was available, which constrained our analysis to one simulation from each model. The limited sampling and temperature biases in models could have resulted in uncertainty in temperature simulations. We obtained paired factual and counterfactual ensemble means of monthly 2 m air temperature and relative humidity from 1990 to 2018, which were then bilinearly interpolated to the GPS coordinates of the DHS clusters.

See **Online** for appendix

### Data analysis

Our data analysis was structured into four key steps (appendix pp 3–7, 24). Briefly, we first established the exposure–response relationships by country and region. A generalised linear model with a natural spline function of average temperature during pregnancy was used to establish these exposure–response relationships. The model adjusted for a set of covariates: maternal education, residence (urban or rural), family wealth, maternal BMI, infant sex, parity, maternal age, month of birth, and the relative humidity during pregnancy. The covariates were identified using a directed acyclic graph (appendix p 25), and the basic model was constructed as in equation 1:

$$g(Y)=\beta_0+ns(\text{temperature},2)+\beta_1{*}\text{education}+\beta_2{*}\text{residence}+\beta_3{*}\text{wealth}+\beta_4{*}\text{BMI}+\beta_5{*}\text{sex}+\beta_6{*}\text{parity}+ns(\text{age},3)+ns(\text{month},4)+ns(\text{humidity},3)$$

where g is the link function (gaussian was used when the outcome was birthweight, whereas logit was used when the outcome was low birthweight), $Y$ is the outcome (birthweight or low birthweight), and *ns* is the natural spline.

Second, we estimated the association between heat and cold exposure during pregnancy and birthweight. Due to the non-linear relationship between temperature and birthweight (identified in the previous analysis[8,11]), we categorised average temperature during pregnancy into ten deciles, with the less than 10th percentile defined as cold and the greater than 90th percentile as hot. The optimal temperature range—corresponding to the lowest risk of reduced birthweight or low birthweight—was determined from the established exposure–response relationships and used as a reference. We then used generalised estimating equations to estimate the association between heat and cold exposure during pregnancy and birthweight or low birthweight. The regression coefficients (β) or odds ratios (ORs), along with their 95% CIs, were used to indicate the mean change in birthweight (in grams) and the odds of low birthweight associated with heat and cold exposure compared with the optimal temperature range, respectively.

Third, we calculated the population attributable risk proportion for heat-related and cold-related low birthweight, as well as the contribution of anthropogenic climate change. The population attributable risk proportion serves as a composite indicator that considers both the exposure proportion and the effects of exposure to assess the overall population impact. To determine the exposure proportion, we calculated the percentage of the population exposed to heat and cold temperatures during pregnancy under both factual and counterfactual scenarios across the six DAMIP models. For the effects of exposure, we assumed that the effect coefficients from the generalised estimating equation models followed a normal distribution and applied Monte Carlo simulation to generate 1000 samples of model coefficients. We then calculated the population attributable risk proportion for heat-related and cold-related low birthweight using equation 2 and derived 2·5% and 97·5% empirical CIs from the empirical distribution of 1000 simulations. The relative risk in equation 2 was transformed from OR:

$$PARP=P_e{*}(RR-1)/[P_e{*}(RR-1)+1]$$

where PARP is the population attributable risk proportion and $P_e$ is the exposure proportion.

The contribution of anthropogenic climate change was qualified as the difference between the population attributable risk proportion for heat-related and cold-related low birthweight under the factual scenario and the population attributable risk proportion under the counterfactual scenario. Additionally, we used equation 3 to calculate the attributable proportion of anthropogenic climate change, indicating the extent to which anthropogenic climate change affects temperature-related low birthweight. Given the uncertainties in climate models and effect estimates, Sobel sensitivity analysis was conducted to assess the uncertainties in both the generalised estimating equation models and the DAMIP climate models:

$$AP_{anthropogenic}=\frac{PARP_{\text{factual}}-PARP_{counterfactual}}{\text{maximum}(PARP_{factual},PARP_{counterfactual})}{*}100\%$$

where AP is the attributable proportion and PARP is the population attributable risk proportion.

Fourth, we estimated the net number of temperature-related low birthweight cases attributable to anthropogenic climate change by summarising heat-related and cold-related low birthweight cases attributable to anthropogenic climate change across all studied countries from 2000 to 2018, combining Lanscan population data and WHO national birth rate data. The 95% CIs for low birthweight related to anthropogenic climate change were estimated in the same manner as described previously.

## Subgroup analyses

Given the large proportion of infants living in rural locations, the significance of poverty in the risk of low birthweight, and the potential role of the season of birth as an important modifier, we conducted a series of subgroup analyses stratified by urban versus rural residence, family wealth, and warm versus cold seasons. Additionally, we hypothesised that elevation might be a key factor driving spatial variation in the estimated association and attribution. Based on the elevation of the included areas, we divided the studied samples into high-altitude (>1000 m) and middle-altitude to low-altitude (≤1000 m) groups. The analyses described previously, including the establishment of exposure–response relationships and the estimation of associations and attributions, were performed within each altitude subgroup.

## Sensitivity analyses

To address potential biases and evaluate the robustness of the association between temperature exposure during pregnancy and birthweight or low birthweight, we performed a series of sensitivity analyses.

Differences in demographic characteristics between inclusion and exclusion groups could introduce selection bias, potentially affecting our association estimates. To address this, we constructed marginal structure models using inverse probability weights and inverse probability selection weights to evaluate the association between heat and cold exposure during pregnancy and birthweight and low birthweight. This approach allowed us to account for potential selection bias and known confounders, providing a likely unbiased estimation of the association. Further details on this method can be found in our previous study.[32]

Some data in the DHS surveys were collected retrospectively, which could introduce recall bias. To explore this, we restricted the sample to data from 1 year to 5 years before the study and the latest two rounds of surveys to re-estimate the associations. Additionally, in LMICs, many infants are born at home, where delayed measurement of birthweight is common, leading to potential outcome misclassification. To address this, we conducted a reanalysis after excluding 41 630 home births. To account for potential bias from self-reporting, we re-estimated the associations using only data for which birthweight was recorded from written records rather than self-reports. Recognising that self-reported information by teenage mothers could be biased due to social pressure or lack of knowledge of reproduction, we repeated the analysis excluding those younger than 18 years. Moreover, since birthweight in the DHS surveys can be rounded to the nearest 100 g, resulting in misclassification, we introduced random errors ranging from –100 g to 100 g, in increments of 10 g, and added these to the original birthweights. Using the simulated birthweights, we reanalysed the associations between heat and cold exposure during pregnancy and birthweight or low birthweight. Finally, to assess the impact of different temperature definitions, we used alternative cutoff values (eg, 5th or 25th percentiles for cold and 95th or 75th percentiles for heat) and re-estimated the associations.

We conducted a sensitivity analysis by restricting the sample to full-term births with gestational ages of 9 months or 10 months to assess whether the observed association between heat and cold exposure and birthweight or low birthweight was influenced by preterm birth. We also ran a series of models, including an unadjusted model, a model adjusted for the minimum adjustment set (including the mother's country of residence, month of birth, relative humidity during pregnancy, urban–rural residence, family wealth, and maternal education), a model with additional covariates (maternal age, BMI, parity, and infant sex), and also a model that further included year of birth, to test the sensitivity of the association between heat and cold exposure and low birthweight to covariate adjustment. To assess the potential impact of unmeasured confounding factors, we calculated the E-value[33] for each estimated association. The E-value represents the minimum strength of association, on the risk ratio scale, that an unmeasured confounder would need to have with both the exposure and the outcome, conditional on the measured covariates, to fully explain a specific exposure–outcome association.

| | Non-low birthweight (n=391 969) | Low birthweight (n=119 480) |
|---|---|---|
| Birthweight, g | 3341·37 (549·76) | 2247·34 (346·49) |
| Gestational age, months | 9·02 (0·29) | 8·98 (0·42) |
| Infant sex | | |
| Male | 206 064 (52·6%) | 56 706 (47·5%) |
| Female | 185 905 (47·4%) | 62 774 (52·5%) |
| Parity | 2·90 (2·06) | 2·42 (1·79) |
| Maternal age, years | 26·26 (6·14) | 25·01 (5·69) |
| BMI, kg/m² | | |
| <18·5 | 34 875 (8·9%) | 22 243 (18·6%) |
| 18·5–25·0 | 180 500 (46·0%) | 61 532 (51·5%) |
| >25·0 | 68 942 (17·6%) | 15 859 (13·3%) |
| Missing | 107 652 (27·5%) | 19 846 (16·6%) |
| Residence | | |
| Urban | 146 984 (37·5%) | 37 434 (31·3%) |
| Rural | 244 985 (62·5%) | 82 046 (68·7%) |
| Maternal education, years | | |
| <6 | 95 189 (24·3%) | 34 445 (28·8%) |
| 6–9 | 125 834 (32·1%) | 29 888 (25·0%) |
| 10–12 | 141 888 (36·2%) | 47 037 (39·4%) |
| >12 | 29 052 (7·4%) | 8110 (6·8%) |
| Missing | 6 (<0·1%) | 0 |
| Family wealth index | | |
| Poorest | 56 610 (14·4%) | 23 388 (19·6%) |
| Poorer | 65 466 (16·7%) | 24 257 (20·3%) |
| Middle | 72 090 (18·4%) | 23 298 (19·5%) |
| Richer | 78 055 (19·9%) | 22 128 (18·5%) |
| Richest | 88 347 (22·5%) | 20 382 (17·1%) |
| Missing | 31 401 (8·0%) | 6027 (5·0%) |
| Season of birth | | |
| Warm | 194 852 (49·7%) | 59 615 (49·9%) |
| Cold | 197 117 (50·3%) | 59 865 (50·1%) |
| Region | | |
| Eastern Africa | 69 371 (17·7%) | 10 930 (9·1%) |
| Central Africa | 26 813 (6·8%) | 3224 (2·7%) |
| Southern Africa | 87 100 (22·2%) | 15 501 (13·0%) |
| Southern Asia | 122 283 (31·2%) | 71 937 (60·2%) |
| Western Africa | 86 402 (22·0%) | 17 888 (15·0%) |

Data are n (%) or mean (SD).

***Table:* Characteristics of the studied population between non-low birthweight and low birthweight newborns**

## Role of the funding source

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

## Results

Among the 511 449 newborns from 31 countries, recorded from 1990 to 2018, 119 480 (23·4%) were low birthweight.

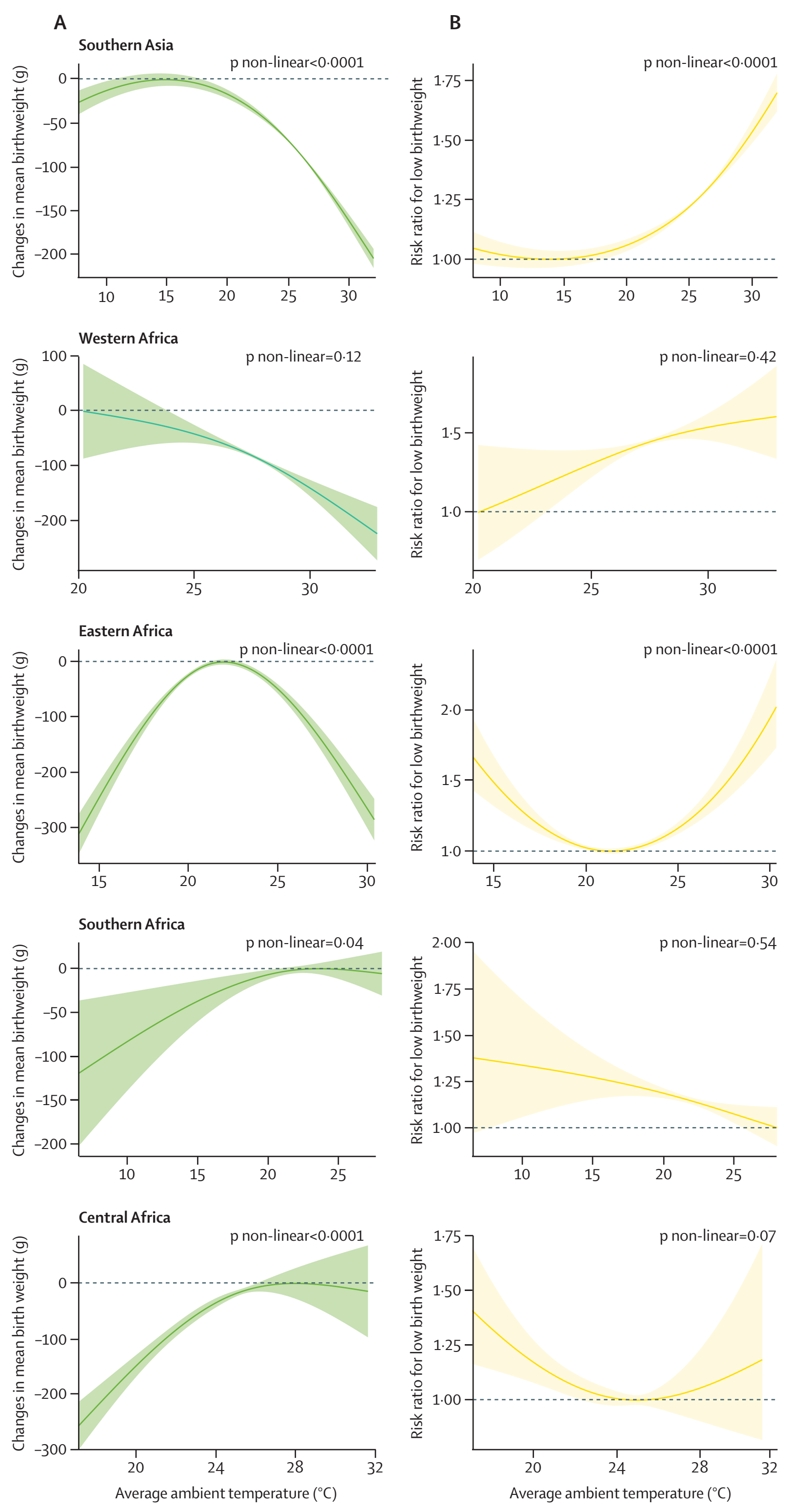

***Figure 1:* The exposure–response curves for average temperature during pregnancy**
(A) Exposure–response curves for mean birthweight. (B) Exposure–response curves for low birthweight in different regions. The generalised linear models were used to depict the exposure–response relationships. Shading represents the 95% CI, and p non-linear less than 0·05 indicates that the exposure–response relationship is non-linear.

Infants born to younger mothers, less educated mothers, those with low BMIs, with less family wealth, or those living in rural areas were more likely to be low birthweight (table).

Temperature exposure during pregnancy varied substantially across the study regions. The average temperature during pregnancy was highest in western Africa (90th percentile 29·7°C), followed by southern Asia (28·9°C), central Africa (28·2°C), eastern Africa (26·3°C), and southern Africa (25·4°C). Notably, larger differences in average temperature during pregnancy were observed across eastern Africa and southern Asia, with median temperatures of 212°C (IQR 197–232) and 256°C (237–273), respectively (appendix pp 12–13).

The exposure–response curves (appendix pp 26–27) show that the temperature–birthweight (or temperature–low birthweight) relationships varied across countries. We identified three distinct patterns: inverse-U type, typically observed in Ethiopia, Tanzania, and Kenya, where both high and low pregnancy temperatures were associated with reduced birthweight or increased low birthweight risk; rising type, typically seen in Namibia, Zambia, and Zimbabwe, where birthweight increased (and low birthweight risk decreased) with rising pregnancy temperatures; and declining type, found in Ghana, Guinea, and Côte d'Ivoire, where birthweight decreased (and low birthweight risk increased) with higher pregnancy temperatures. These patterns were consistent across the five geographical regions (figure 1). Accordingly, we classified the associations into heat risk type (southern Asia and western Africa), cold risk type (central Africa and southern Africa), and heat and cold risk type (eastern Africa).

We categorised average temperature during pregnancy into ten deciles and selected the optimal temperature range as the reference (appendix p 14). Figure 2 illustrates the associations between heat and cold exposure during pregnancy and birthweight (or low birthweight) in different regions. In areas classified as heat risk type, high-temperature exposure was the dominant risk factor for reduced birthweight or low birthweight. Compared with the reference temperature range (<10th percentile), exposure to heat (>90th percentile) was associated with mean birthweight reductions of –137·39 g (95% CI –150·58 to –124·21) in south Asia and –70·93 g (–96·70 to –45·16) in western Africa, along with an increased risk of low birthweight (OR 1·41, 95% CI 1·34 to 1·48 in southern Asia, and 1·12, 1·02 to 1·24 in western Africa). In cold risk type regions, low-temperature exposure was the primary risk factor for reduced birthweight or low birthweight. Cold exposure was associated with birthweight reductions of –84·62 g (95% CI –137·91 to –31·32) in central Africa, and –40·19 g (–72·27 to –8·10) in southern Africa, with corresponding low birthweight risk of OR 1·31 (95% CI 1·10 to 1·56) and OR 1·18 (1·02 to 1·36), respectively. Eastern Africa, identified as a heat and cold risk type region, showed that both heat and cold exposures were associated with

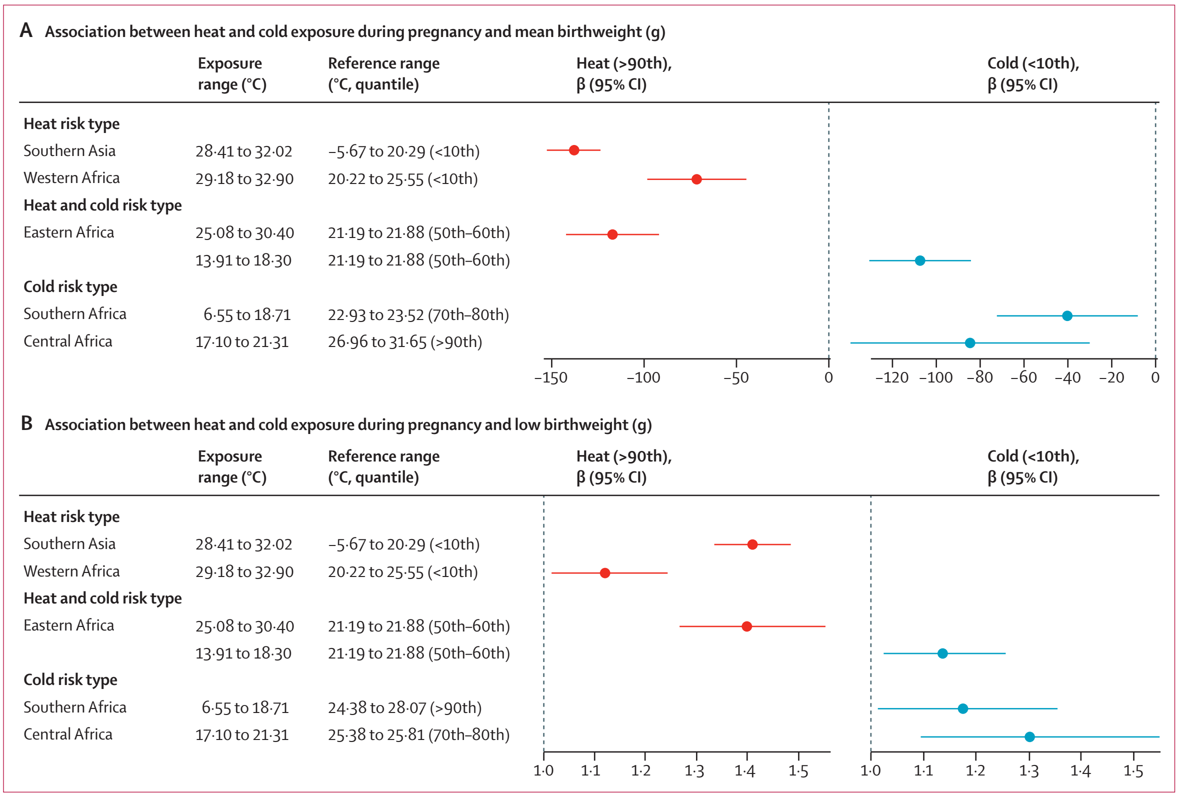

*Figure 2:* **Associations between heat and cold exposure during pregnancy and birthweight (or low birthweight) in different regions**
The 10th and 90th percentiles of average temperature during pregnancy were used as the thresholds of defining cold and heat exposure, respectively. For each region, the optimal temperature range—corresponding to the lowest risk of reduced birthweight or low birthweight—was determined from the established exposure–response relationships and used as a reference. The generalised estimation equation with an exchangeable working correlation was applied to estimate the associations. A series of covariates, including maternal education, residence, family wealth, maternal BMI, infant sex, parity, and country, were added to the generalised estimation equation for adjustment. The mother ID was added as the random effect. Meanwhile, the maternal age (df=3), the month of birth (df=4), and the relative humidity during pregnancy (df=3) were controlled by using spline functions. (A) β indicates the mean birthweight change associated with heat or cold exposure, using the optimal temperature range as the reference. (B) The odds ratio of low birthweight associated with heat or cold exposure, using the optimal temperature as the reference.

reduced birthweight (–116·73 g [95% CI –140·89 to –92·57] for heat and –107·02 g [–130·20 to –83·84] for cold) and higher low birthweight risk (OR 1·40 [1·27 to 1·55] for heat and 1·14 [1·02 to 1·26] for cold), with the 50th–60th temperature range as the reference. The country-specific associations between heat and cold exposure during pregnancy and birthweight and low birthweight by country are summarised in the appendix (pp 28–29).

From 1990 to 2018, higher climate mean temperatures were observed in southern Asia and western Africa, while relatively lower values were seen in the other three regions (figure 3). The annual mean temperature across all study sites showed an increasing trend from 1990 to 2018. The simulated temperature under the factual scenario (based on DAMIP's historical climate simulations) aligned well with observed temperatures (figure 3). By contrast, the counterfactual scenario (based on DAMIP's hist-nat climate simulations without anthropogenic forcing) showed lower temperatures and no increasing trend, highlighting the dominant role of anthropogenic forcing in climate change over the study region. The historical temperature simulations from DAMIP models exhibited lower deviations from Climate Research Unit data in eastern and western Africa, whereas deviations were higher in southern Asia (appendix p 30).

Low birthweight rates ranged from 8·7% in Rwanda to 37·4% in India (figure 4). Overall, anthropogenic climate change significantly contributed to temperature-related low birthweight, although the impact varied considerably across regions. In heat risk type regions (ie, southern Asia and western Africa), prenatal heat exposure caused 2·4% (95% CI 1·7–3·6) and 1·1% (0·2–2·6) of total low birthweight, with 59·2% (3583 of 6052 cases, 95% CI 16·6–94·3) and 89·0% (982 of 1103 cases, 51·0–100·0) of heat-related low birthweight attributed to human-induced climate change (appendix pp 15–16). In cold risk type regions (central Africa and southern Africa), prenatal cold exposure caused 2·7% (95% CI 0·8–5·5) and 1·3% (0·1–2·9) of total low birthweight, with 53·3% (2998 of 5625 cases, 21·5–88·8) and 63·1% (1068 of 1693 cases, 34·0–88·7) of the cold-related low birthweights avoided

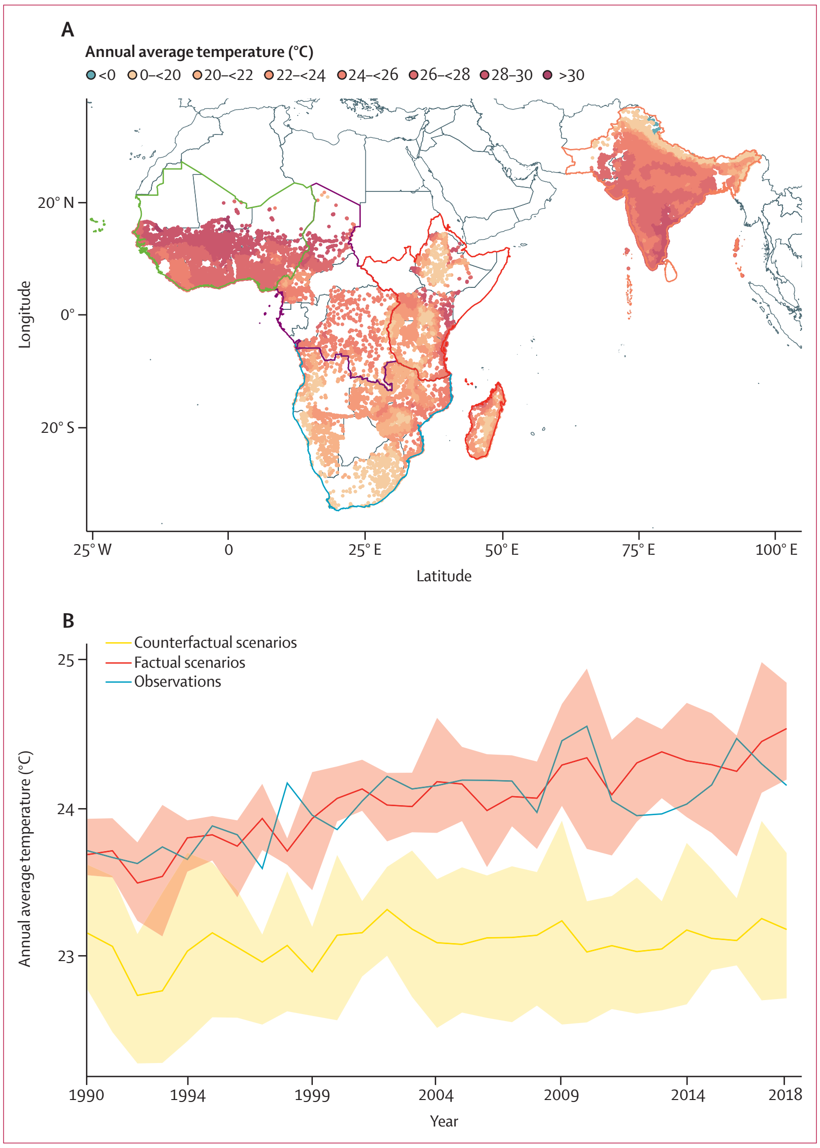

***Figure 3:* Anthropogenic climate change across the study region**
(A) Spatial distribution of annual average temperatures in the 31 countries included in the study. Orange represents southern Asia, red eastern Africa, green western Africa, purple central Africa, and blue southern Africa. (B) Annual average temperatures from 1990 to 2018 using Climatic Research Unit gridded Time Series temperature data (blue line), DAMIP factual scenario data (red line), and counterfactual scenario data (yellow line). The shadowed areas represent the range of maximum and minimum annual average temperatures across six DAMIP climate simulations. DAMIP=Detection and Attribution Model Intercomparison Project.

due to human-induced climate change. In the heat and cold risk type region (eastern Africa), prenatal heat and cold exposure caused 3·9% (95% CI 2·1–8·1) and 1·0% (0·2–2·0) of total low birthweight, respectively (appendix p 17). Anthropogenic climate change contributed to 77·3% (2899 of 3750 cases, 27·0–100·0) of heat-related low birthweight while preventing 64·5% (1061 of 1645 cases, 36·4–90·0) of cold-related low birthweight.

The uncertainty in cold-related low birthweight due to climate change is mainly driven by the hist-nat and generalised estimating equations models, with the hist model having a minor impact. For heat-related low birthweight, uncertainty varies by region: southern Asia and eastern Africa show lower uncertainty due to consistent heat effects, whereas in western Africa, both the hist and generalised estimating equations models significantly contribute to uncertainty (appendix p 18).

In most parts of southern Asia, western Africa, and the coastal areas of eastern Africa, human-induced climate change increased the low birthweight burden, with the Ganges Plains in southern Asia being the most affected, where anthropogenic climate change-related low birthweight exceeded 250 per grid (2500 km²; figure 5). Conversely, in most parts of central and southern Africa and the inland areas of eastern Africa, human-induced climate change reduced the low birthweight burden, with the most significant reduction observed in the Ethiopian and East African Plateau, where the minimum anthropogenic climate change-related low birthweights were 250 or less per grid. As expected, a significant temporal change was also observed, with anthropogenic climate change-related low birthweights increasing in most parts of western Africa, central Africa, and eastern Africa during 2010–18 compared with 2000–09.

In southern Asia and eastern Africa, infants from low-income and middle-income families faced a higher risk of reduced birthweight due to heat exposure, whereas in central Africa, they faced a higher low birthweight risk due to cold exposure during pregnancy (appendix p 31). In southern Asia, western Africa, and eastern Africa, infants living in urban areas were more vulnerable to heat exposure, whereas in southern Asia and western Africa, infants born in the warm season faced a higher low birthweight risk (appendix p 31).

Elevation was a significant factor influencing the spatial variation in the estimated associations and attributions (appendix p 32). In high-altitude areas (>1000 m), birthweight increased with rising pregnancy temperature, with exposure to cold temperatures being the dominant risk factor for reduced birthweight and low birthweight (β –40·0 g, 95% CI –61·3 to –18·8 and OR 1·17, 95% CI 1·07 to 1·28). In the low-altitude and middle-altitude areas, heat exposure posed a greater risk of lower birthweight than in the high-altitude areas. As altitude increased, anthropogenic climate change-related low birthweights gradually decreased to zero at 1000 m, with negative anthropogenic climate change-related low birthweights observed at altitudes greater than 1000 m. However, since most pregnant individuals in our study lived in low-altitude and middle-altitude regions, they were more vulnerable to heat and human-induced climate change.

The results from the inverse probability-weighted marginal structural model (appendix p 18) aligned well with our main findings, indicating a limited influence of potential selection bias. To address potential recall bias, we restricted the sample to a shorter recall period, which reduced the possibility of misclassification but also

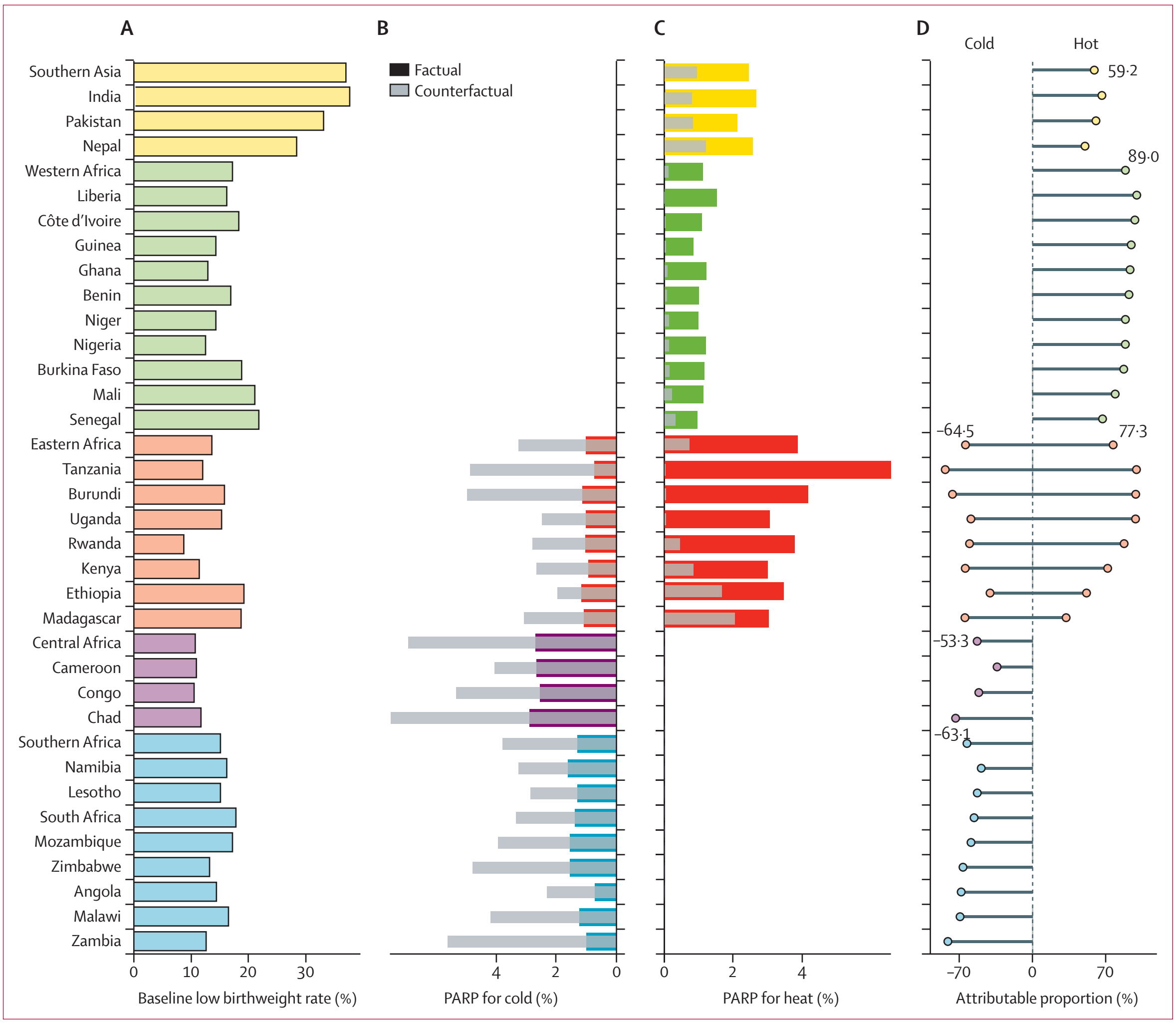

***Figure 4:* Heat-related and cold-related low birthweight attributable to anthropogenic climate change in the studied population**
(A) Low birthweight rates in 31 countries. (B) PARP for cold: PARP, indicating the proportion of low birthweight associated with heat exposure in factual scenarios (coloured bars) and counterfactual scenarios (grey bars). (C) PARP for heat: the proportion of low birthweight associated with cold exposure in factual scenarios (coloured bars) and counterfactual scenarios (grey bars). (D) Attributable proportion of the PARP, indicating the extent to which anthropogenic climate change affects low birthweight associated with heat or cold exposure during pregnancy (appendix pp 15–17). PARP=population attributable risk proportion.

decreased the sample size, leading to wider CIs for the estimated association (appendix pp 19–20). Excluding births for which birthweight was self-reported, home births, and births to mothers younger than 18 years did not alter the associations (appendix p 21). Using simulated birthweights, we found that rounding birthweights to 100 g increments in the DHSs did not affect the association estimates (appendix p 22). Moreover, our main findings remained consistent when using different thresholds to define heat or cold exposure (appendix pp 33–36).

Limiting the sample to full-term deliveries confirmed that the observed associations between heat and cold exposure and birthweight or low birthweight were not dependent on preterm birth (appendix p 22). Various modelling strategies indicated that the associations were robust to covariate adjustments (appendix p 23). Finally, the calculated E-values suggested that unmeasured confounders were unlikely to significantly influence our findings (appendix p 37).

## Discussion

This study investigated the relationship between anthropogenic climate change, temperature exposure during pregnancy, and birthweight across 31 countries in southern Asia and sub-Saharan Africa. Our analysis revealed robust associations between maternal heat and cold exposure during pregnancy and an increased risk of reduced birthweight and low birthweight. Furthermore, we quantified the contribution of anthropogenic climate change to low birthweight associated with heat and cold exposure during pregnancy. We found that the associations and contributions varied spatially, depending on the underlying climate state (ie, the mean climate

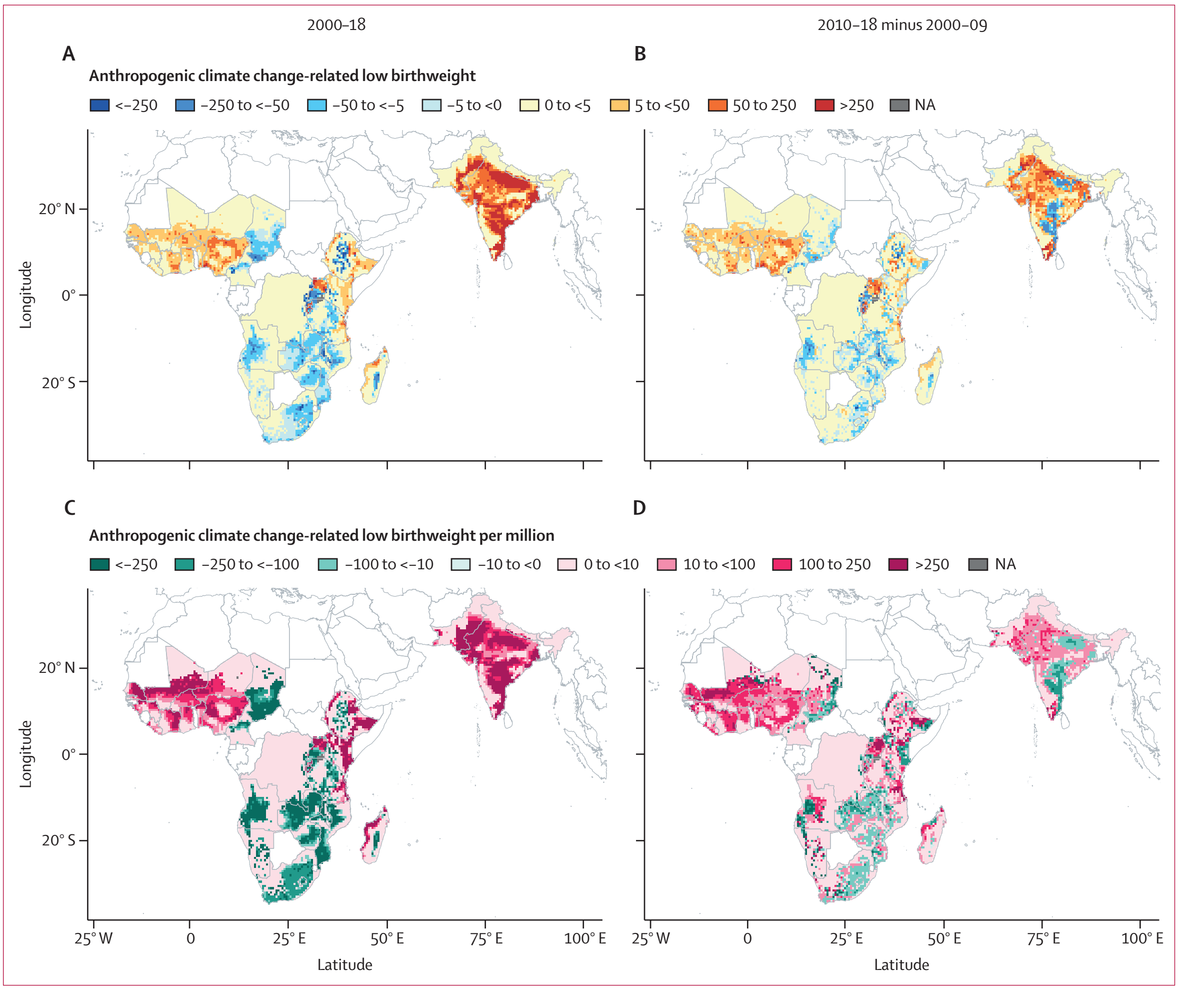

*Figure 5:* **The net numbers of temperature-related low birthweight cases attributable to anthropogenic climate change**
(A) The spatial pattern of temperature-related low birthweight cases attributable to anthropogenic climate change during 2000–18. (B) Differences in anthropogenic climate change-related low birthweight between 2010 and 2018 and between 2000 and 2009 (the former minus the latter). (C) The spatial pattern of the ratio of anthropogenic climate change-related low birthweight to the baseline population during 2000–18. (D) Differences in the ratio of low birthweight related to anthropogenic climate change to the baseline population between 2010 and 2018 and between 2000 and 2009 (the former minus the latter). NA=not available.

temperature) in different regions. Our study offers novel insights into the impact of human-induced climate change on birthweight, providing valuable information for shaping climate mitigation and adaptation strategies in LMICs and reducing global health inequalities.

Focusing on LMICs, we found that both heat and cold exposure were associated with lower birthweight than optimal temperatures, consistent with previous studies from high-income countries.[8,11,13] Several underlying biological mechanisms could explain how non-optimal environmental temperatures affect birthweight: high temperatures increase cardiovascular strain, potentially damaging cells, the placenta, and the vascular system, thus disrupting uterine blood flow and nutrient exchange. This disruption can lead to fetal undernutrition, low birthweight, and congenital malformations.[3,4] Cold temperatures cause vasoconstriction and blood thickening, increasing cardiovascular stress similarly to heat exposure.[5] Both heat and cold exposure during pregnancy are linked to oxidative stress and systemic inflammation.[6,7] Excessive oxidative stress and hyperinflammatory placental state can damage cellular structures, impair placental function, and ultimately lead to fetal growth restriction.[8,9]

The extensive geographical coverage of the DHS dataset enabled us to evaluate spatial patterns in these associations. We identified three distinct patterns: heat risk type (southern Asia and western Africa), cold risk type (central Africa and southern Africa), and combined heat and cold risk type (eastern Africa). To validate our findings, we conducted a series of sensitivity analyses to address potential selection, information, and confounding biases, and found that the associations and spatial patterns remained consistent. Although the association remained robust when using more extreme temperature percentiles as thresholds to define heat and cold exposure, the CIs widened. This suggests that to accurately assess the low birthweight risks associated with non-optimal temperatures, we must comprehensively consider population exposure intensity and proportion. Additionally, unmeasured confounding remains a challenge in establishing true causality in observational studies. For example, activities and heat adaptation behaviours among pregnant individuals, which could serve as potential confounders, were not accounted for. Future research should aim to collect data on these and other relevant variables to strengthen the analysis.

Studies have increasingly focused on attributing the impact of heat on population health to climate change, particularly in distinguishing the contribution of human-induced climate change.[22–24] For example, a multi-country study found that 1·6% of deaths in the warm season were due to heat exposure, and 37·0% of these heat-related deaths were attributable to global warming caused by human activities.[24] Another study, in Switzerland, reported that 3·5% of all-cause summer deaths were related to high temperatures, with 60% attributed to anthropogenic climate change.[22] Similarly, a study in China estimated that heatwave exposure caused an average of 13 262 preterm births annually between 2010 and 2020, with 25·8% of these preterm births attributable to human-induced climate change.[25] In our study, we found that from 2000 to 2018, human-induced climate change contributed significantly to temperature-related low birthweight. However, the impact varied considerably across regions. In southern Asia and western Africa (heat risk type), approximately 59·2% and 89·0% of heat-related low birthweights were attributed to human-induced climate change, respectively. Notably, in eastern Africa, where both heat and cold temperatures influence birthweight, the attribution proportion of anthropogenic climate change was low. This does not imply a weak impact; rather, it suggests that anthropogenic climate change increased the low birthweight burden associated with heat exposure while reducing the burden associated with cold exposure, effectively neutralising the overall contribution. These findings suggest that focusing solely on heat when attributing health burdens to climate change might be insufficient. However, given the projected increases in temperature, in the future the number of low birthweight cases attributable to heat is expected to rise substantially, whereas the reduction in cases due to decreased cold exposure is anticipated to be comparatively modest.

Elevation could play a crucial role in explaining the spatial variation in these associations and the contribution of anthropogenic climate change. Temperature decreases by approximately 6°C for every km above sea level, and we found that when elevation exceeded 1000 m, the association between temperature and birthweight was no longer predominantly driven by heat. Furthermore, with increasing elevation, the available land area decreases, reducing life opportunities. Population density and birth rate also contribute to the spatial heterogeneity of the human-induced low birthweight burden. By 2050, the population of sub-Saharan Africa is estimated to reach 2123 million (22% of the global population), while the population of southern Asia is expected to increase to 2254 million (23% of the global population).[34] Without additional adaptation measures and climate actions, we project that 219 000 and 53 600 infants with low birthweights will be born in southern Asia and western Africa, respectively, by 2050 due to human-induced climate change.

We found that southern Asia, western Africa, and the coastal regions of eastern Africa—particularly densely populated, low-altitude urban areas—were significantly impacted by anthropogenic climate change. Urban greening initiatives, such as the creation of parks, playgrounds, and roadside vegetation, should be prioritised to mitigate the urban heat island effect in these areas. Additionally, the use of reflective surfaces, such as white roofs, can help to reduce daytime temperatures.[35] Our study highlights that impoverished pregnant individuals in both urban and rural areas were disproportionately affected by high temperatures. This increased vulnerability is likely due to their lower adaptation capacity, making them more susceptible to the adverse effects of heat. Routine health examinations and comprehensive prenatal care for these groups who are at high-risk are critical for early detection of heat-related risks. Furthermore, the Loss and Damage Fund, established during the 28th Conference of the Parties, is designed to provide financial assistance to vulnerable LMICs for losses resulting from meteorological disasters and climate events.[36] This fund can help LMICs mitigate and adapt to current and future climate change-related health risks. Our findings will guide responses to specific loss and damage scenarios, promote climate justice, and contribute to reducing global health inequalities.

This study has several limitations. First, despite our thorough exploration of potential biases, so important confounding factors remain inaccessible, meaning that our findings reflect associations rather than establishing true causality. Second, this study only assessed the impact of non-optimal temperatures in the context of climate change, whereas climate change can also lead to other events, such as changing rain patterns, extreme weather, floods, wildfires, dust and desert storms, and increased ozone levels.[37] Therefore, the low birthweight cases attributable to anthropogenic climate change could have been largely underestimated. Furthermore, we used the average temperature during pregnancy to define heat or cold exposure, which reflects semi-chronic exposure to hot or cold environments. This approach might not adequately have captured the effects of extreme temperatures, such as heatwaves and cold spells. Third, inherent uncertainty in climate models necessitates cautious interpretation of the quantitative estimates of low birthweight burden attributable to anthropogenic climate change, particularly in southern Asia, where temperature simulations showed relatively high deviations from Climate Research Unit data. Furthermore, the DHS data have inherent limitations. The birth dates, recorded at the month level, and participants' residential addresses, available at the cluster level, lack precision, potentially leading to exposure misclassification. However, this misclassification is likely random, which could introduce bias towards the null association. The retrospective nature of DHS data also introduces the risk of recall bias, and birthweights from home births could be inaccurate due to a lack of scales or delayed measurement. These issues can result in unreliable birthweight data and outcome misclassification, potentially affecting the accuracy of association estimates. However, our multiple sensitivity analyses suggest these issues were unlikely to substantially influence our findings. Moreover, this study covered 31 LMICs in sub-Saharan Africa and southern Asia, where specific ethnicities and cultural practices could influence how individuals perceive and respond to heat and cold stress, potentially limiting the generalisability of the findings.

In conclusion, exposure to heat and cold during pregnancy was associated with an increased risk of low birthweight. Anthropogenic climate change contributed to an increased low birthweight burden associated with heat but decreased the low birthweight burden associated with cold. Southern Asia, western Africa, and the coastal areas of eastern Africa bear the heaviest burden, largely due to their basic climate state (ie, climate mean temperature) and population density. Our findings have important implications for global public health by identifying vulnerable areas and populations for which climate change poses major risks to early-life health. Furthermore, our study can guide the allocation of the Loss and Damage Fund to populations most affected by climate change-related health risks and inform climate mitigation and adaptation strategies in LMICs.

### Contributors

QW was responsible for the study design and study conception. ZZ and TZ were responsible for data preparation. ZZ was responsible for data analysis. TB, LDK, QW, LX, CH, and SY were responsible for interpreting the results. ZZ and TZ wrote the first draft. QW and ZZ edited the second draft. All coauthors revised the manuscript together and approved the final version. HW, XC, and MW had access to and verified the underlying data. All authors had full access to all the data in the study and had final responsibility for the decision to submit for publication.

### Declaration of interests

We declare no competing interests.

### Data sharing

All datasets relevant to this study are publicly available including the population data, the Climatic Research Unit temperature datasets, the European Centre for Medium-range Weather Forecasts Reanalysis (version 5) humidity datasets, the factual and counterfactual scenario datasets from the Detection and Attribution Model Intercomparison Project, the LandScan program, which is the source of global population data, the national crude birth rates, the global elevation data, and the R code and data used to replicate this paper.

For the **population data** see https://www.idhsdata.org/idhs/

For the **Climatic Research Unit temperature datasets** see https://crudata.uea.ac.uk/cru/data/hrg/

For the **European Centre for Medium-range Weather Forecasts Reanalysis (version 5) humidity datasets** see https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5

For the **factual and counterfactual scenario datasets from the Detection and Attribution Model Intercomparison Project** see https://esgf-node.llnl.gov/search/cmip6/

For the **LandScan program** see https://landscan.ornl.gov/

For the **national crude birth rates** see https://data.worldbank.org/

For the **global elevation data** see https://www.ncei.noaa.gov/

For the **R code and data used in this study** see https://github.com/ZhenghongZhu/Estimating-the-burden-of-temperature-related-low-birth-weight-attributable-to-anthropogenic-climate-

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