On the Health Impacts of Climatic Shocks: How Heatwaves Reduce Birthweight in Sub-Saharan Africa

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Heatwaves are among the most important global public health challenges of our time. Yet we know little about how exposure to heatwaves (as opposed to hot days) affects health at birth, which is a key contributor to health, development, and well-being in later life. This study addresses this shortcoming by investigating the relationship between in utero exposure to heatwave and birthweight by assessing both the timing and mechanisms of heatwave effects. I use novel georeferenced survey data on birth and pregnancy outcomes from the latest round of the Demographic and Health Surveys to link the birth outcomes of 64,210 infants across 11 sub-Saharan African countries with high-resolution daily climate data. I find that infants exposed to heatwave in the third trimester of gestation had significantly lower birthweight and that this effect is mediated by reduced gestational age at birth instead of reduced intrauterine growth. The effect of heatwave is concentrated among male babies and mothers with no or little formal education. By highlighting how exposure to environmental conditions early in life shapes health outcomes with far-reaching consequences, the findings carry lessons for policymakers to protect pregnant women from heatwave exposure to mitigate the negative impact of climate change.

Introduction

Shocks affecting pregnant women can adversely affect the health at birth of their offspring (Almond and Currie 2011; Torche 2011), with consequences for their development and well-being during childhood and adulthood (Conley, Strully, and Bennett 2003). Previous literature suggests that in utero shocks have more severe and longer-lasting effects than those occurring during early childhood (Almond and Currie 2011). Shocks affecting pregnant women can have long-lasting effects on the health, education, and socioeconomic outcomes of their offspring (Torche 2011; Almond

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2006; Song 2013) and even the children of their offspring (Cook, Fletcher, and Forgues 2019; Lee 2014).

Extreme climate events are dramatic shocks with the potential to affect mothers' and their children's health at birth. Heatwaves are among the most threatening types of shocks and are expected to increase in frequency, intensity, and duration in the coming years (IPCC 2014, 2019). This study, therefore, focuses on the effect of in utero exposure to heatwave on infants' birthweight in sub-Saharan Africa (SSA)—a region that is exceptionally vulnerable to climate variability and change.

Birthweight is an important health outcome for several reasons. First, birthweight is a marker of early health status. In particular, low birthweight and preterm birth are leading causes of neonatal and infant mortality as well as risk factors for stunted growth during childhood (WHO 2005; UNICEF and WHO 2019; Christian et al. 2013). Second, birthweight has effects on the development and well-being during childhood and adulthood. It is correlated with chronic diseases in adulthood, including hypertension, coronary heart disease, obesity, and diabetes (Jornayvaz et al. 2016; Barker 2004). Birthweight also positively correlates with outcomes that are not directly health related like early cognition and children's development, educational attainment, employment, and earnings (Currie and Hyson 1999; Case, Fertig, and Paxson 2005; Conley and Bennett 2000; Boardman et al. 2002; Gu et al. 2017). Finally, the negative effects of low birthweight are not restricted to one generation, but they can persist intergenerationally: prior research finds that mothers with low birthweight are significantly more likely to have low birthweight babies (Currie and Moretti 2007).

The relationship between birthweight and short- and long-run health, education, and socioeconomic outcomes suggests that the heatwave effect on birthweight may have dramatic consequences for population health and well-being. The consequences may be particularly severe for the poor who are disproportionately vulnerable to climate extremes as a result of the global warning (IPCC 2014, 2019). Heatwaves may thus exacerbate global health and socioeconomic inequalities.

This analysis overcomes three main limitations of existing scholarship on the effect of in utero exposure to climate extremes on birthweight. First, existing studies mainly focus on maternal exposure to hot days (Deschênes, Greenstone, and Guryan 2009; Davenport, Dorélien, and Grace 2020; Grace et al. 2021; 2015) or positive rainfall shocks (Rocha and Soares 2015) thus largely overlooking the effects of *heatwaves*, which are periods of several consecutive hot days (Perkins 2015). Going beyond prior research, I focus on the impact of heatwaves on birthweight in SSA. SSA is a largely rural and agrarian context that is highly vulnerable to heatwaves and has a high incidence of low birthweight. I take advantage of the Demographic and Health Survey (DHS) that only recently made available more comprehensive information on birth and pregnancy outcomes. It presents a novel opportunity to study exposure to heatwave on birthweight during the gestation period.

Second, so far only one study has investigated the impact of heatwaves on birthweight. In contrast to this study by Andalón et al. (2016), I did not only investigate the impact of heatwaves on birthweight but also comprehensively analyze the timing and underlying mechanisms of this effect. Regarding the underlying mechanisms, I assess which of two known mechanisms affecting birthweight is driving the effect of heatwaves: reduced gestational age at birth or intrauterine growth restriction (IUGR; also referred to as small for gestational age at birth) or a combination of both (Kramer 1987a, 1987b). Regarding the timing, I assess whether the effect of heatwaves on birthweight depends on the trimester of gestation during which the heatwave occurs. Taken together, this study is the first to provide insights into the underlying mechanisms and the timing of heatwaves on birthweight.

Third, prior research provides evidence that sociodemographic characteristics such as maternal education or socioeconomic status can moderate the negative health consequences of climate-related events (Dimitrova and Muttarak 2020; Conte Keivabu and Cozzani 2022). That is, climate-related events affect different subgroups of the population differently. This article extends this line of scholarship by examining whether the effects of heatwaves are socially stratified or experienced equally by all mothers and children regardless of their sociodemographic characteristics. Understanding the vulnerabilities to heatwaves for different socioeconomic groups is a prerequisite for targeted policy intervention.

Taken together, this study expands current knowledge about the in utero exposure to heatwave on birthweight by addressing the *timing* and *mechanisms* of heatwave effects, and whether these effects are stratified by key socioeconomic characteristics. To do so, I use georeferenced survey data from the DHS to link the birth outcomes of 64,210 infants across 11 SSA countries with fine-grained daily climate data on heatwave events. I then apply a fixed-effects strategy to provide the first evidence on the causal impacts of in utero exposure to heatwave on birthweight in SSA. This study thus not only investigates the causal effect of heatwaves on birthweight but advances our understanding of when during the gestation (first, second, and third trimesters) heatwave is more critical, and the extent to which gestational age and uterine growth contribute to the effect of heatwave exposure on birthweight.

Heatwave and birthweight: Mechanisms and timing

Although it is widely acknowledged that biological, social, behavioral, and environmental factors can affect birthweight, scholars have rarely explored how weather shocks—particularly heatwaves—impact birthweight. I, therefore, propose a conceptual framework that illuminates how exposure to heatwave might impact birthweight in low- and middle-income contexts. This framework is based on the premise that heatwaves operate through a set of *direct* and *indirect* determinants to exert an impact on birthweight. Because the timing of exposure to shocks during gestation is important in determining its impact on birthweight, I discuss *how* and *when* heatwaves affect gestational age and intrauterine growth to influence birthweight. Drawing on existing literature, I hypothesize that an effect of disease would be mediated by intrauterine growth restriction and concentrated during the first trimester of gestation, while an effect of undernutrition would be concentrated during the second or third trimesters of gestation. Alternatively, if the effect of heatwave is mediated by reduced gestational age and concentrated in the first or third trimester, heatwaves can induce stress which is another determinant of birthweight.

Mechanisms

Stress has been considered as the main consequence of heatwave for pregnant women. While this may be true in high-income countries, it is not necessarily the case in low-income rural contexts and specifically in SSA, where most people rely on weather-sensitive activities for their livelihoods (World Meteorological Organization 2020), and climate-sensitive diseases are responsible for the majority of childhood deaths (Perin et al. 2022; World Health Organization 2009). Stress, undernutrition, and altered disease environment, therefore, are the indirect factors that explain how in utero exposure to heatwave affects gestational age at birth and uterine growth, the two immediate determinants of birthweight (Kramer 1987a, 1987b).

First, stress is found to trigger, in both the mother and the fetus, the production of hormones such as corticotrophin-releasing hormone, adrenocorticotrophic hormone, and cortisol, which are related to premature delivery and low birthweight (Glynn et al. 2001; Hobel 2004; Lockwood 1999; Hobel et al. 1999). Heat also stimulates the release of antidiuretic hormone and oxytocin which is a key hormone regulating the onset of delivery (Fuchs et al. 1982; Dreiling, Carman, and Brown 1991). Previous research finds that heat exposure during pregnancy decreases gestational length and increases the probability of giving preterm birth (Andalón et al. 2016; Barreca and Schaller 2020). This suggests that by shortening gestational age, heat stress may reduce birthweight. Some support also exists for a stress effect on intrauterine growth restriction (Wadhwa et al. 2004), which is driven by the release of the corticotrophin-releasing hormone. The release of the corticotrophin-releasing hormone is associated with decreased uteroplacental flow and hypoxemia, which are known risk factors for IUGR.

Second, high-temperature extremes can affect harvests which may lead to reductions in maternal nutritional intake, affecting birthweight.

Empirical research shows that prolonged extreme temperatures cause the greatest damage to cultivation and remarkably increase evapotranspiration rates and water stress (Rebetez et al. 2006), which often translates into lower yields and higher food prices. For example, Lobell et al. (2011) show for African maize that for each degree above 30°C yields decrease by 1 percent. These negative effects on agricultural productivity may contribute to household food insecurity—and, consequently, inadequate food intake by the pregnant woman—and income constraints (Hoegh-Guldberg et al. 2018), both of which are underlying causes of undernutrition (UNICEF 2013). Maternal nutrition, in particular, is considered as the most important factor for determining the weight of an infant at birth and a major intrauterine environmental factor in the fetal development, particularly in "developing countries" (Kramer 1987a, 1987b; Ramakrishnan et al. 2012). Empirical studies find evidence that improving the nutrition and income of low-income families leads to both increases in birthweight and decreases in the fraction of births that are low birthweight (Almond, Hoynes, and Schanzenbach 2011; Hoynes, Page, and Stevens 2011). As for mechanisms, the negative effects of nutritional disruptions in utero on birthweight are often attributed to IUGR (Almond and Mazumder 2011; Almond, Hoynes, and Schanzenbach 2011; Hoynes, Page, and Stevens 2011), although there is some support for a mediating effect of preterm birth: prior research documents heightened serum cortisol levels among pregnant women fasting during Ramadan (Dikensoy et al. 2009) which are in turn associated with preterm birth (Bandoli et al. 2018).

Third, heatwave can affect birthweight by altering the disease environment. In general, temperatures affect the transmission cycle of vector-borne, water-borne, and food-borne diseases (Patz et al. 2003). Although extreme temperatures are often lethal to disease-causing pathogens (Patz et al. 2003), they also increase the prevalence of enteric pathogens associated with diarrhea. For example, during the 1997–1998 El Niño episode—when the mean ambient temperature in Lima increased up to 5°C above normal—the number of daily admissions for diarrhea increased to 200 percent of the expected rates (Checkley et al. 2000). Diarrheal illness during pregnancy is associated with a higher risk of small-for-gestational-age infants (Newman et al. 2019). A possible mechanism through which diarrhea in pregnancy may cause small-for-gestational-age infants may be through maternal malnutrition and undernutrition as diarrhea reduces the capacity to absorb nutrients and fluids. Another possible mechanism is through increased susceptibility to new infections that lead to impaired intrauterine growth. Inflammation resulting from infections may also play a role through impaired growth pathways and reduced nutritional transfer from mother to fetus (Boeuf et al. 2013; Conroy et al. 2013; Ashorn et al. 2018). For example, evidence suggests that malaria and influenza infections in pregnancy adversely affect intrauterine growth (Schlaudecker, Steinhoff, and Moore 2011; Briand et al. 2016; Moore et al. 2017). Research from the Kenyan Highlands also shows a close association between unusually high maximum temperatures and malaria transmission (Githeko and Ndegwa 2001).

Timing

Several studies have suggested that the timing of exposure to shocks during pregnancy is important in determining its impact on birthweight, but it is still not clear in which trimester of gestation shocks are most consequential. A large set of studies argues that exposure to stress in early gestation—first trimester—leads to decreased birthweight (Camacho 2008; Torche 2011; Mansour and Rees 2012; Torche and Shwed 2015; Brown 2018; Foureaux Koppensteiner and Manacorda 2016; Currie, Mueller-Smith, and Rossin-Slater 2018; Guantai and Kijima 2020). Similarly, studies suggest that malaria infection during the first trimester of pregnancy is associated with low birthweight (Valea et al. 2012; Huynh et al. 2011). If these mechanisms are the most important, exposure to heatwave during the first trimester of pregnancy would have the largest effects on birthweight. Alternatively, animal studies find that by decreasing placental weight, heat stress in *late* gestation may lead to placental insufficiency and ultimately low birthweight (Collier et al. 1982). Indeed, it is also plausible that late pregnancy could be the most important window for the heatwave relationship to birth outcomes. This is consistent with previous research highlighting that the adverse effects of undernutrition on birthweight are the strongest in the later stages of pregnancy (Lumey 1998; Painter, Roseboom, and Bleker 2005; Strauss and Dietz 1999; Lawton et al. 1988). Nonetheless, other studies find that second trimester undernutrition specifically is relatively more detrimental to birthweight than third trimester undernutrition (Darling 2017). This is mainly because the bulk of fetal growth occurs most rapidly in the second trimester and is most vulnerable to interferences related to maternal nutrition. If these pathways dominate, we would expect births with second or third trimester exposure to heatwave to be most reactive.

Data and variables

I combine datasets from two sources: (1) georeferenced microlevel health and socioeconomic data from the DHS and (2) georeferenced climate data from the ERA5 archive provided by the European Centre for Medium-Term Weather Forecasting (ECMWF).

The georeferenced microlevel data come from the woman's questionnaire of the DHS of 11 countries in SSA. The DHS Program collects representative data on population, health, fertility, and socioeconomic characteristics from over 90 low- and middle-income countries. The questionnaire—which is reviewed and modified in each of the seven phases of The DHS Program—forms the basis for the questionnaire that is applied in each country, and its standardization ensures comparability over time and across populations. Importantly for this study, the DHS also reports the GPS latitude and longitude coordinates of communities (also called *clusters*) where women reside, which allows linking interviewed women (and their children) to their geographic location at the time of survey. To preserve confidentiality, urban clusters are randomly spatially displaced up to 2 km; rural clusters up to 5 km, with a further 1 percent of rural clusters randomly spatially displaced up to 10 km from their actual locations. I account for this random displacement by assuming that the cluster can be located anywhere within a 10-km radius of the GPS latitude and longitude coordinates provided.[1] I make no distinction between clusters—whether urban or rural—to make the data consistent and comparable across individuals.

The climate dataset retrieved from the ECMWF's ERA5 archive[2] contains data for every hour since January 1, 1979, on a global grid of parallels and meridians at a 0.25×0.25-degree resolution—about 30 km at the equator (Hersbach and Dee 2016). I extract data on maximum air temperature for every hour from January 1, 1979, to December 31, 2019, and for every weather grid cell (ERA5 cells) across all the 11 SSA countries. These data are then used to calculate heatwave events across DHS clusters, as I will discuss below. I also extract data on rainfall to control for a measure of exposure to precipitation during the gestation period. The advantage of these climate data is that they are reanalyzed using various sources such as satellites, radars, weather stations, aircraft, ships, buoys, and radiosondes and are thus more suitable for spatiotemporally consistent environmental analyses than gauge data in areas with poor station data availability (Hersbach et al. 2019; Zandler, Senftl, and Vanselow 2020).[3]

For this study, I use all DHS from the latest phase (Phase VII) available in early 2020 containing information on the woman's geographic location (i.e., GPS latitude and longitude coordinates) and the time of residence in the cluster (Angola 2015, Benin 2017, Burundi 2016, Ethiopia 2016, Malawi 2015, Mali 2018, Nigeria 2018, South Africa 2016, Uganda 2016, Zambia 2018, and Zimbabwe 2015). The advantage of the latest phase of DHS is that, unlike previous survey rounds that only included information on the woman's child's month and year of birth, the woman's questionnaire also includes for the first time questions on both the day of birth and the duration of pregnancy for all her births.[4] This information is important in this type of research for two main reasons. First, because the measure of the treatment is meant to cover the period of pregnancy, the date of birth and the duration of pregnancy are essential to ensure correct temporal matching between the heatwave events and the pregnancy period. Previous studies that use DHS data to examine in utero exposure to climate extremes do not use information on the child's date of birth and gestational length, thus making inferences about the child's conception based on the child's month and year of birth and/or the assumption that all pregnancies are 40 weeks (or nine months) in duration. However, not all pregnancies are 40 weeks in duration: preterm births account for 11.1 percent of the world's live births, and this percentage increases to 18 percent in some African countries (Blencowe et al. 2012). Second, information on the duration of pregnancy further allows me to create measures of gestational age and intrauterine growth and thus identify the mechanism of heatwave effects. The analytical sample includes all children born to interviewed women in the five-year period preceding the survey; this is done to avoid recall bias due to omission and backward displacement of births (Pullum et al. 2013; Schoumaker 2011).

Another crucial aspect of the DHS is that it contains information on women's length of residence in the current cluster. This question allows me to merge geocoded information about a maternal cluster of residence during pregnancy with geocoded information about maximum air temperature across ERA5 cells to produce a measure of the treatment during pregnancy. All women who have lived in the current cluster at least one year before their child's birth are included in the analysis because the weather conditions they were exposed to during pregnancy can be inferred.[5]

Dependent variables

The main dependent variable used in the analysis is birthweight measured in grams. To determine which proximate mechanism is at play in the relationship between heatwave and birthweight, I use as additional dependent variables for gestational age at birth and uterine growth: gestational age measured in months, and uterine growth measured as the gestational age-specific birthweight percentile (using separate birthweight distributions by sex). These variables are also dichotomized to produce measures of low birthweight (<2,500 g), preterm delivery (<9 months), and intrauterine growth restriction (birthweight below the 10th percentile of the weight distribution by gestational age). This is done to examine whether exposure to heatwave increases the proportion of births most vulnerable to poor health and poor developmental outcomes rather than simply altering mean birthweight within a plausibly optimal range.

Finally, birthweight data were reported for 52 percent of babies in the data, with the majority of the missing birthweight information concentrated among children of rural (i.e., 54 percent) and noneducated respondents (i.e., 69 percent), a pattern that is in line with prior research on birthweight in Mali (Grace et al. 2021). I find some variation in the reporting of birthweight by country. In Ethiopia and Nigeria, information on birthweight is more likely to be missing than in other countries, with about 79.2 percent to 80.6 percent of births having no birthweight recorded. As a supplementary analysis, I estimate the model on the sample excluding Ethiopia and Nigeria and find that results are quantitatively the same. Additionally, I find no variation in birthweight reporting by month of conception. In further analysis, I also find that exposure to heatwave does not affect the probability of missing data in the birthweight variable which suggests that there is no pattern of missingness that correlates with exposure to heatwave.[6] We can therefore be confident that missingness does not upward bias the main results. If anything, the concentration of missing birthweight data among certain segments of the population likely downward biased the results and therefore does not threaten the validity of the results.

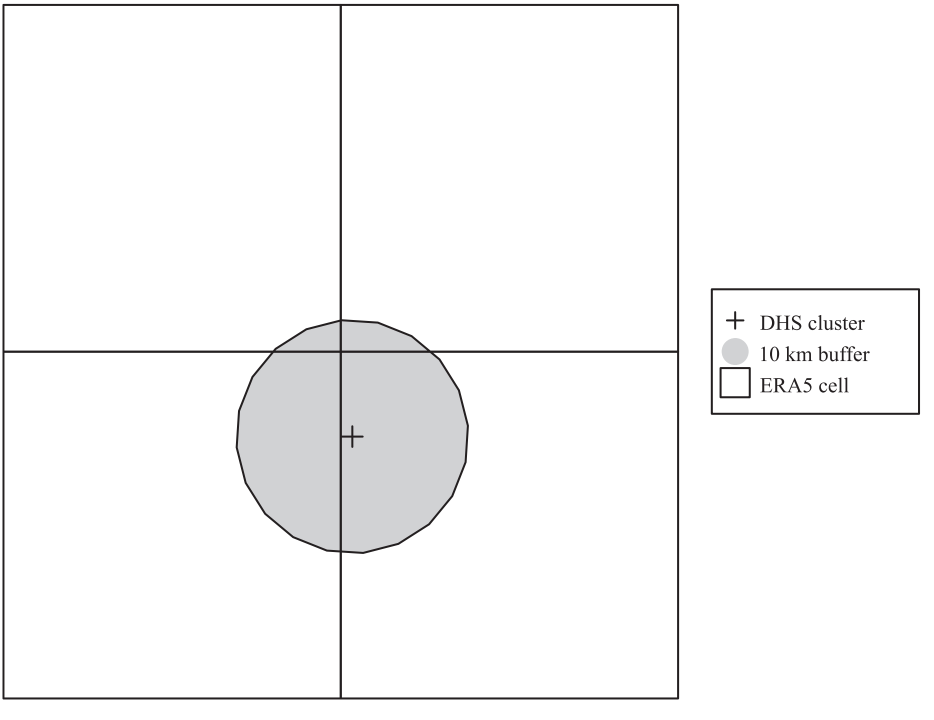
Treatment variable

The main treatment is exposure to heatwave during each trimester of gestation, constructed as 1–12 weeks after conception for the first trimester, 13–26 weeks after conception for the second trimester, and 27–40 weeks after conception for the third trimester. In the scholarly literature, a heatwave consists of consecutive days above certain temperature cutoffs that can either be location based (relative cutoff) or physiologically based (absolute cutoff) (Robinson 2001; Perkins 2015; Perkins and Alexander 2013). Following previous studies that examined the linkages between heat and birthweight (Davenport, Dorélien, and Grace 2020; Deschênes, Greenstone, and Guryan 2009; Grace et al. 2015; 2021), I use an absolute cutoff because it takes into account that certain temperature thresholds are physiologically relevant. I, therefore, define heatwave as periods of three or more consecutive days with a daily maximum temperature greater than 95°F. In further analyses, I allow for flexibility in the definition of heatwave to explore the effects of different degrees of heatwave intensity on birthweight (i.e., over 100°F and 105°F).

Alongside temperature intensity, duration is a core component of heatwaves. It is generally accepted that heatwaves become heatwaves when the days above-defined temperature thresholds last from more than two to more than six consecutive days of extreme heat (Hansen et al. 2008; Nitschke, Tucker, and Bi 2007; Robinson 2001; Tong, Wang, and Barnett 2010; Perkins 2015). Because there are no good theoretical reasons for why we should prefer two to three, four, five, or six days, I opted for the duration of three or more consecutive hot days which provided the lowest Akaike's information criterion and aligns with a large number of previous studies (Perkins-Kirkpatrick and Gibson 2017; Varela, Rodríguez-Díaz, and DeCastro 2020; Kanti et al. 2022; Gosling et al. 2009; Perkins and Alexander 2013; Odoulami et al. 2017; Li 2020). In supplementary analyses (discussed below), I allow again for flexibility in the definition of heatwave to explore the effects of different heatwave duration (i.e., from two to eight consecutive days).

Using the ERA5 dataset on hourly maximum temperature, I identify the daily maximum temperature for all ERA5 cells within the 10-km buffer around the DHS cluster location as illustrated in Figure 1. I then assign to each DHS cluster location a value of daily maximum temperature which I calculated as the average value of daily maximum temperature in all the intersecting ERA5 cells. This is done to account for the error around the GPS latitude and longitude coordinates in the DHS data to capture events that directly impact women and their children. Next, for each child conceived in DHS cluster *e* at time *t*, I create a binary variable for the treatment that equals "1" if the daily maximum temperature exceeds 95°F for three or more consecutive days during each trimester of gestation. I, therefore, do not account for the number of heatwave events in each trimester of gestation but rather measure at least one heatwave that occurred during each trimester of gestation. In addition, because the focus of this paper is on identifying whether the heatwave is more consequential in the first, second, or third trimesters of gestation, a three-day heatwave that breaks over a trimester will not be categorized as a heatwave. Similarly, if the temperature falls below 95°F on any of at least three consecutive hot days, it does not fulfill the definition of a heatwave.

FIGURE 1 Example of buffer (10 km) around DHS cluster and intersecting ERA5 cells



I thus follow the literature in defining heatwaves as binary variables which renders them different from counting hot days. One unavoidable limitation is that binary measures of heatwaves cannot capture the full heatwave exposure and might thus underestimate the impact of heatwaves on birthweight. Following a small number of studies that have complemented their analyses using the length of the longest event (Perkins, Alexander, and Nairn 2012; Perkins and Alexander 2013), I therefore also conduct supplementary analyses investigating the effect of a continuous measure of heatwave exposure during each trimester of gestation on birthweight.

Summary statistics

Table 1 provides descriptive statistics for the full sample, which is composed of 64,210 babies conceived between October 2009 and May 2018 to 49,937 women living across 6,536 clusters. Data are weighted using DHS sample weights. The mean birthweight in the sample is 3,243 g. About 10.4 percent of the children weighed less than 2,500 g at birth, 5.7 percent were born prematurely, and 10.8 percent had a birthweight below the 10th percentile of the weight distribution. Thirty-six percent of children were exposed to a heatwave during at least one trimester of gestation.

Figure 2 shows the temporal (top panel) and spatial (bottom panel) variation in the number of heatwaves across all the 6,536 DHS clusters with at least one woman residing with her child, over the period from October 1, 2009, to May 31, 2018. The number of heatwaves is calculated as the sum of periods of three or more consecutive days with daily maximum temperature exceeding 95°F. The top panel in Figure 2 shows that there is substantial temporal variation. For example, in March 2016, there was a considerable number of clusters with three or more consecutive days with daily maximum temperature exceeding 95°F as the total number of heatwave events across all clusters reached a value of 3,725. In August of the same year, the daily maximum temperature exceeded 95°F for three or more consecutive days in far fewer areas. This variation suggests that babies who were conceived in the same year a few months apart were exposed to different weather even if they had been conceived in the same area. The top panel further shows that the trend in the number of heatwave events across years has varied over time. Before the end of 2015, the number of heatwave events decreased sharply to a minimum value and steeply increased after. From about 2015 onwards, the distribution pattern of heatwave events changed such that the number of heatwaves stays high for a longer period of time during the year, that is heatwaves have become more prevalent in more recent years.

The bottom panel in Figure 2 shows substantial spatial variation in heatwave events with the aggregate number of heatwaves ranging from 0—when no heatwave events occurred between October 1, 2009, and May

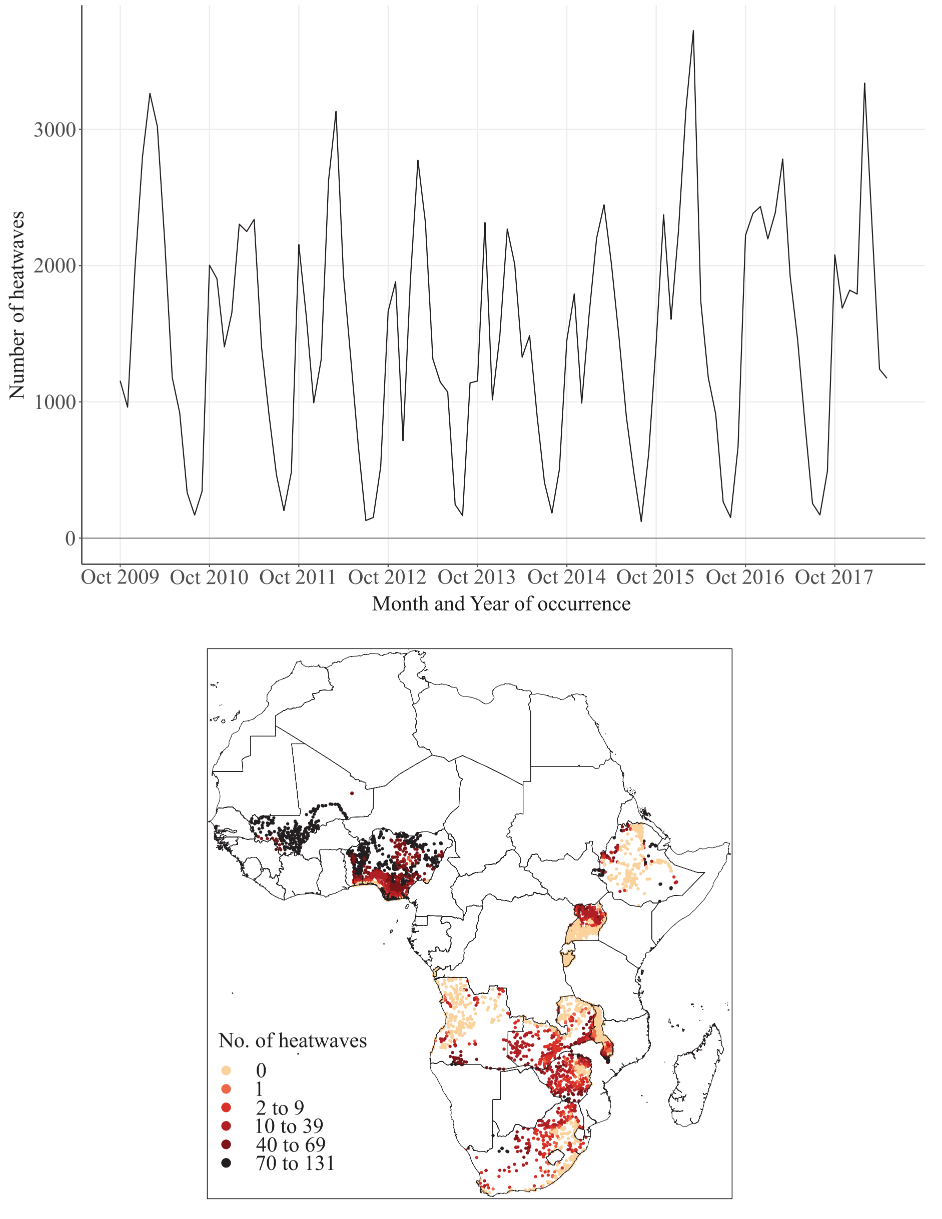
TABLE 1 Descriptive statistics

	Mean/proportion	SD
Birthweight in grams	3243.126	737.687
Birthweight < 2,500 g	0.104	0.307
Born prematurely	0.057	0.252
Intrauterine growth restriction	0.108	0.308
Female	0.488	-
Birth order		
1	0.226	-
2–4	0.535	-
5	0.239	-
Birthweight from written card	0.449	-
Mother's education		
No education	0.167	-
Primary education	0.304	-
Secondary and higher education	0.529	-
Mother's partner's education		
No education	0.114	-
Primary education	0.222	-
Secondary and higher education	0.468	-
Don't know / Missing	0.195	-
Mother's age at birth		
12–20	0.155	-
21–34	0.671	-
35+	0.174	-
Exposure to heatwave during the first trimester	0.196	0.377
Exposure to heatwave during the second trimester	0.214	0.391
Exposure to heatwave during the third trimester	0.209	0.392
Exposure to heatwave at least one trimester during gestation	0.361	0.47
N	64,210	

NOTES: Means and proportions are based on weighted data; *N* is unweighted.
SOURCE: Analysis of author's combined dataset based on all sub-Saharan African Type VII DHS and ERA5 archive (see the Data and Variables section).

31, 2018—to 131—meaning that there were 131 heatwave events over the period of study. It also shows that there is significant within-country variation. For example, Ugandan babies were, on average, more exposed to heatwave if they were conceived by women living in Northern areas compared to babies conceived by women residing in Southern areas, where the aggregate number of heatwaves is much smaller. This suggests that babies who were conceived by women living in the same country in different areas were exposed to different weather even if they had been conceived in the same period.

FIGURE 2 Temporal and spatial variation in the number of heatwaves across DHS clusters from October 1, 2009, to May 31, 2018



NOTES: In the top panel, the number of heatwaves is calculated as the sum of periods of three or more consecutive days in a given month from October 1, 2009, to May 31, 2018, with a daily maximum temperature greater than 95°F. In the bottom panel, the number of heatwaves is calculated as the sum of periods of three or more consecutive days in a given ERA5 cell from October 1, 2009, to May 31, 2018, with a daily maximum temperature greater than 95°F.
SOURCE: As for Table 1.

Empirical strategy

The main analysis of this paper is to assess the effect of *in utero* exposure to heatwave on birthweight and the mechanisms underlying this effect. I use a fixed-effects strategy which exploits: (1) the exogeneity of weather events (Harari and La Ferrara 2018; von Uexkull et al. 2016; Andriano and Behrman 2020) and (2) the temporal variation and seasonal variation in heatwave conditions within each region. The model reads as

$$y_{irt} = \beta_0 + \beta_1 hw_t^1 + \beta_2 hw_t^2 + \beta_3 hw_t^3 + \beta_4 prec_t^1 + \beta_5 prec_t^2 + \beta_6 prec_t^3 + x_i^{'}\beta_7 + \alpha_{ry} + \alpha_{rm} + \varepsilon_{irt}, \quad (1)$$

where y_{irt} is the individual outcome variable (birthweight, gestational age, uterine growth, etc.) from a region of residence r at time t; hw_t^1, hw_t^2, and hw_t^3 are exposure to heatwave during the first, second, and third trimesters, respectively. Child and mother control, x_i', include child's sex, birthweight recorded in a written card,[7] mother's educational attainment (categorized as no education, primary education, and secondary and higher education), mother's partner's educational attainment (categorized as no education, primary education, secondary and higher education, and don't know and missing; the latter implicitly controls for women's marital status as this question is not asked to women who are not in a union at time of the survey), type of residence (urban vs. rural community), and mother's age at birth (categorized as 12–20, 21–34, and 35+). I also include a measure of exposure to precipitation (measured as total precipitation) during the first, second, and third trimesters ($prec_t^1$, $prec_t^2$, and $prec_t^3$, respectively) as well as region-by-year-of-conception and region-by-month-of-conception fixed effects (α_{ry} and α_{rm} respectively)[8]. The use of region-by-year-of-conception and region-by-month-of-conception fixed effects allows us to account for region-specific temporal and seasonal trends. I use weights to make the results representative of babies living in these 11 countries in SSA and cluster standard errors by region to allow for the correlation of error terms across babies born in the same region.[9] Linear regression models are estimated for continuous outcomes and linear probability models are estimated for binary outcomes.

The heatwave variables are calculated over the 40-week interval starting from the time of conception which is based on the child's date of birth minus the length of gestation. I then assign the exposure in each trimester of gestation (i.e., first, second, and third) following conception irrespective of gestational length (Torche and Shwed 2015). It is crucial to take into account the variation in the length of gestation across pregnancies instead of counting retrospectively three trimesters from the child's date of birth to be able to measure exposure in each trimester (Foureaux Koppensteiner and Manacorda 2016). This approach also removes the selection bias induced by mothers with shorter gestational lengths being less exposed to heatwave.

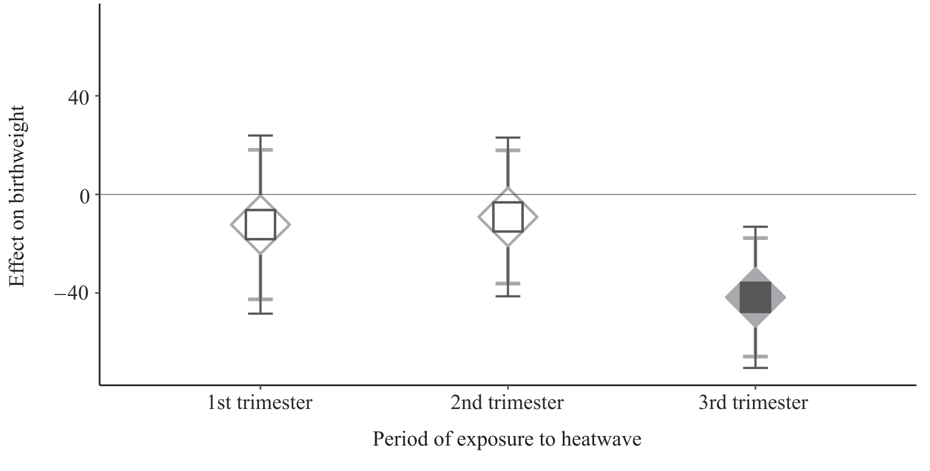
Results

Birthweight

This section presents results of the effect on birthweight of exposure to heatwave during gestation. Figure 3 displays the effects of heatwave on birthweight across the three periods of exposure—first, second, and third trimesters—and the 90 and 95 percent confidence intervals (Table A1 in the online Appendix presents parameter estimates, standard errors, and significance tests).

Exposure in the third trimester of gestation significantly reduces birthweight whereas exposure in the first and second trimesters does not have any significant effects on birthweight. Being exposed to heatwave during the third trimester of gestation reduces birthweight by 41.8 grams, which is substantively relevant compared to exposure to other environmental shocks as I will discuss below. Note that I used a conservative measure of heatwave exposure which defines heatwaves as three consecutive days where the temperature exceeds 95°F. For purposes of robustness, I repeat the analysis of heatwave to explore the effects of different degrees of intensity and duration of heatwave. I have used 20 additional definitions of heatwave where intensity varies between 95, 100, and 105°F and duration ranges from two to eight consecutive hot days. The results as displayed in

FIGURE 3 Effect of heatwave on birthweight by a period of exposure



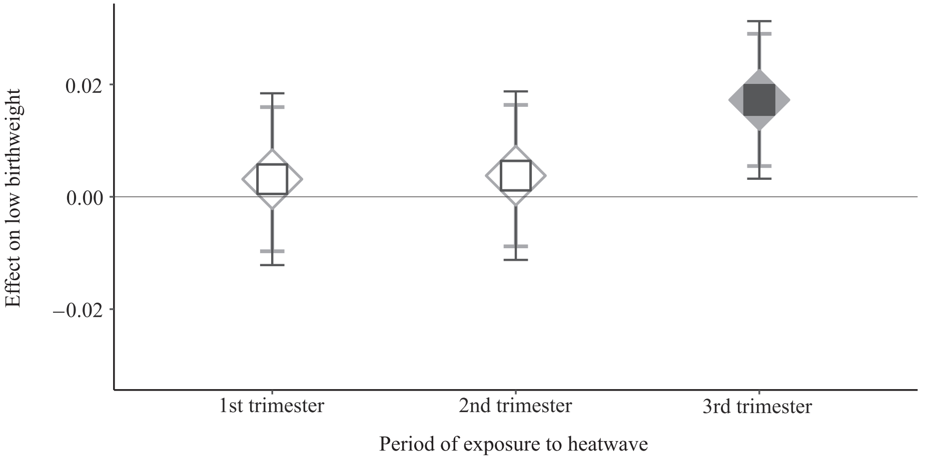
NOTES: Obtained from parameter estimates in Table A1. Dots indicate parameter estimates; light and dark gray vertical bars are the 90 and 95 percent confidence intervals, respectively; and dots colored light and dark gray indicate estimates significant at the 10 and 5 percent levels, respectively. Exposure to heatwave is calculated over the 40-week interval starting from the month of conception and estimated as the effect of exposure to heatwave at different stages of pregnancy, that is, first, second, and third trimesters. Data are weighted to make the results representative of babies living in these 11 countries in SSA, and standard errors are clustered by region.
SOURCE: As for Table 1.

Figure A1 in the online Appendix show that heatwaves reduce birthweight regardless of definitions; the higher the heatwave intensity, the more substantive its impact on birthweight reduction. However, definitions vary in the extent to which they reach statistical significance at conventional levels. In additional supplementary analyses, I also define heatwaves as continuous variables (i.e., number of consecutive days over 95, 100, and 105°F) and find that the longer heatwaves last, the stronger their impact on birthweight losses (see Figure A2 in the online Appendix).

Low birthweight

The previous section has shown that exposure to heatwave during the third trimester significantly reduces birthweight by 41.8 grams. However, heatwave might only decrease birthweight within a normal range but does not increase the proportion of low-weight births to such an extent that will likely cause health and developmental problems later in life. In this section, I show that this is not the case. To address this question, Figure 4 presents the results for the effects of low birthweight across the three periods of exposure—first, second, and third trimesters—and the 90 and 95 percent confidence intervals (Table A2 in the online Appendix presents parameter estimates, standard errors, and significance tests). Figure 4 shows that the probability of low birthweight among children exposed during the third

FIGURE 4 Effect of heatwave on low birthweight by period of exposure



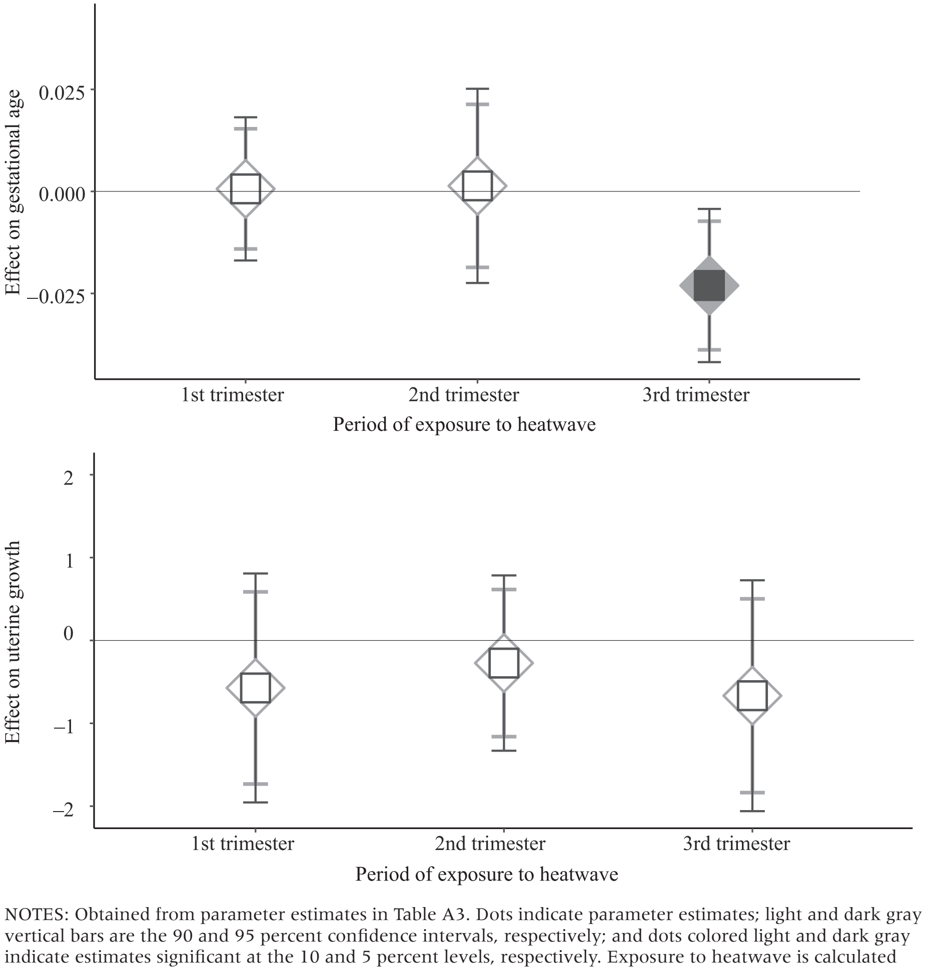
NOTES: Obtained from parameter estimates in Table A2. Dots indicate parameter estimates; light and dark gray vertical bars are the 90 and 95 percent confidence intervals, respectively; and dots colored light and dark gray indicate estimates significant at the 10 and 5 percent levels, respectively. Exposure to heatwave is calculated over the 40-week interval starting from the month of conception and estimated as the effect of exposure to heatwave at different stages of pregnancy, that is, first, second, and third trimesters. Data are weighted to make the results representative of babies living in these 11 countries in SSA, and standard errors are clustered by region.
SOURCE: As for Table 1.

trimester of gestation significantly increases by 1.7 percent. This finding suggests that exposure to heatwave during pregnancy reduces birthweight to such an extent that it could cause health and developmental problems later in life.

Gestational age and uterine growth

As discussed, the effect of heatwave exposure on birthweight depends on only two proximate determinants of birthweight: gestational age and uter-

FIGURE 5 Effect of heatwave on gestational age (top) and uterine growth (bottom) by period of exposure



NOTES: Obtained from parameter estimates in Table A3. Dots indicate parameter estimates; light and dark gray vertical bars are the 90 and 95 percent confidence intervals, respectively; and dots colored light and dark gray indicate estimates significant at the 10 and 5 percent levels, respectively. Exposure to heatwave is calculated over the 40-week interval starting from the month of conception and estimated as the effect of exposure to heatwave at different stages of pregnancy, that is, first, second, and third trimesters. Data are weighted to make the results representative of babies living in these 11 countries in SSA, and standard errors are clustered by region.
SOURCE: As for Table 1.

ine growth. In order to explore the underlying mechanisms, the effects of heatwave on gestational age and gestational age–specific birthweight percentile are examined and presented in Figure 5 (Table A3 in the online Appendix presents parameter estimates, standard errors, and significance tests). The top panel presents the effect on gestational age and shows a significant decline in gestational age during the third trimester of gestation, whereas exposure in the first and second trimesters does not have any significant effect on gestational age. These results suggest that the effect of exposure to heatwave on birthweight is at least partly driven by a reduction in gestational age.

The results on uterine growth are presented in the bottom panel. A small and statistically insignificant decline in uterine growth is found among babies exposed to heatwave in the third trimester. As a whole, these results support the hypothesis that the influence of heatwave exposure on birthweight is largely mediated by reduced gestational age.

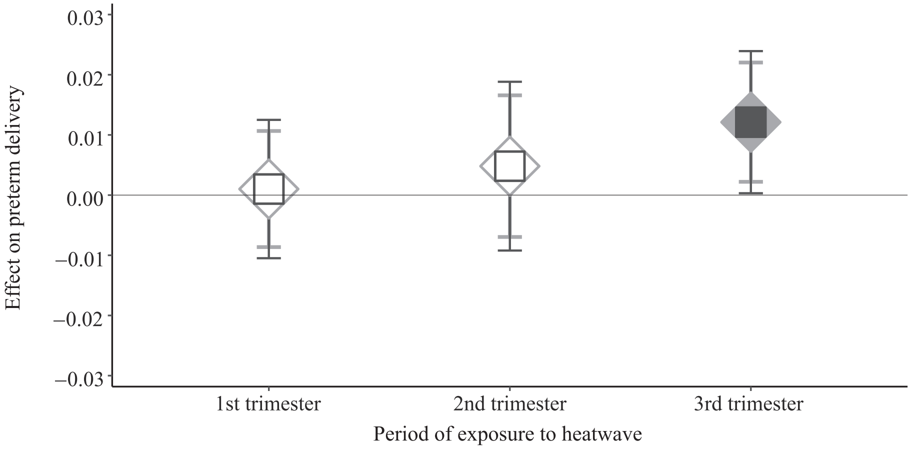
Preterm delivery and intrauterine growth restriction

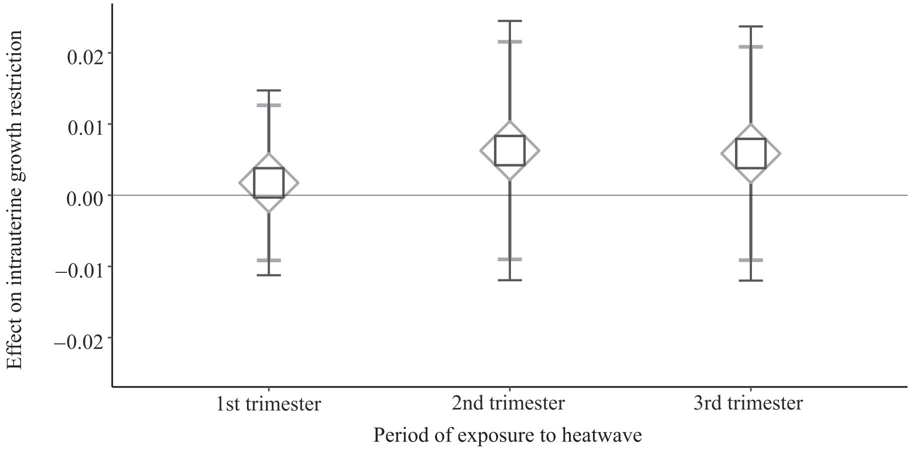
Just like for birthweight, I investigate whether exposure to heatwave increases preterm delivery by using a binary measure of preterm delivery. Figure 6 presents the results for the effects of preterm delivery and intrauterine growth restriction across the three periods of exposure—first, second, and third trimesters—and the 90 and 95 percent confidence intervals (Table A4 in the online Appendix presents parameter estimates, standard errors, and significance tests). The top panel, showing the effect on the probability of preterm birth, indicates an increase of 1.2 percent for children exposed during the third trimester of gestation. Finally, the bottom panel shows that exposure in any of the gestation periods does not significantly affect the probability of intrauterine growth restriction. These findings show that the effect of heatwave exposure on birthweight is driven by an increased probability of preterm delivery.

Differential vulnerabilities

Regardless of climate conditions, babies born into disadvantaged socioeconomic groups are more likely to have lower birthweight than more socioeconomically advantaged babies. Table A1 in the online Appendix shows that girls and babies born to parents without formal educational attainment have on average lower birthweight. It does not follow, however, that these differences reflect differences in heatwave vulnerabilities. I, therefore, apply the demographic differential vulnerability approach (Muttarak, Lutz, and Jiang 2015) to assess whether key demographic and socioeconomic characteristics modify the degree of vulnerability to low birthweight due to maternal exposure to heatwave.

FIGURE 6 Effect of heatwave on preterm delivery (top) and intrauterine growth restriction (bottom) by period of exposure

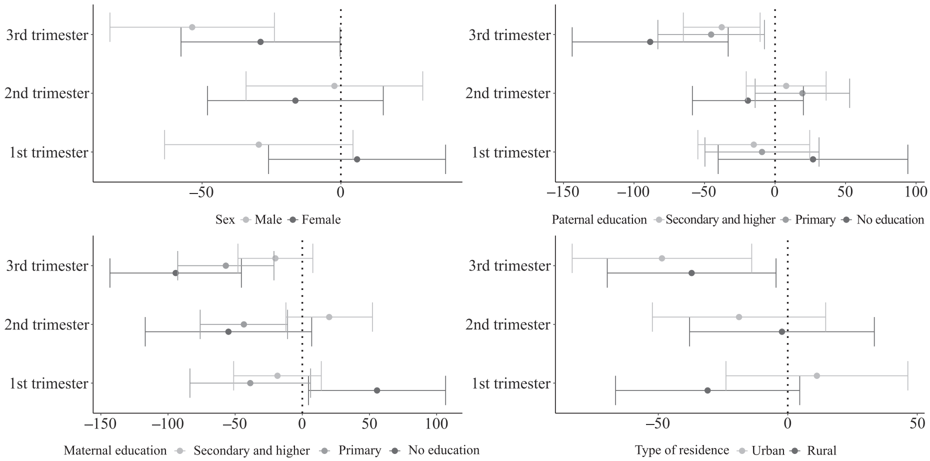




NOTES: Obtained from parameter estimates in Table A4. Dots indicate parameter estimates; light and dark gray vertical bars are the 90 and 95 percent confidence intervals, respectively; and dots colored light and dark gray indicate estimates significant at the 10 and 5 percent levels, respectively. Exposure to heatwave is calculated over the 40-week interval starting from the month of conception and estimated as the effect of exposure to heatwave at different stages of pregnancy, that is, first, second, and third trimesters. Data are weighted to make the results representative of babies living in these 11 countries in SSA, and standard errors are clustered by region.
SOURCE: As for Table 1.

I investigate differential vulnerability to heatwaves empirically by including an interaction term between the treatment variable and key sociodemographic characteristics and by comparing the effect of heatwave between different subgroups of the population. I consider the child's sex, the mother's level of education, the mother's partner's level of education, and the type of residence which are important determinants of climate-related vulnerabilities (Dimitrova and Muttarak 2020). I calculate the results as marginal effects, which measure the change in birthweight as a

FIGURE 7 Effect of heatwave on birthweight by sex, paternal education, maternal education, and type of residence by period of exposure



NOTES: Dots indicate parameter estimates of exposure to heatwave among each subgroup of the population; horizontal bars are the 90 percent confidence intervals. Exposure to heatwave is calculated over the 40-week interval starting from the month of conception and estimated as the effect of exposure to heatwave at different stages of pregnancy, that is, first, second, and third trimesters. Data are weighted to make the results representative of babies living in these 11 countries in SSA, and standard errors are clustered by region.
SOURCE: As for Table 1.

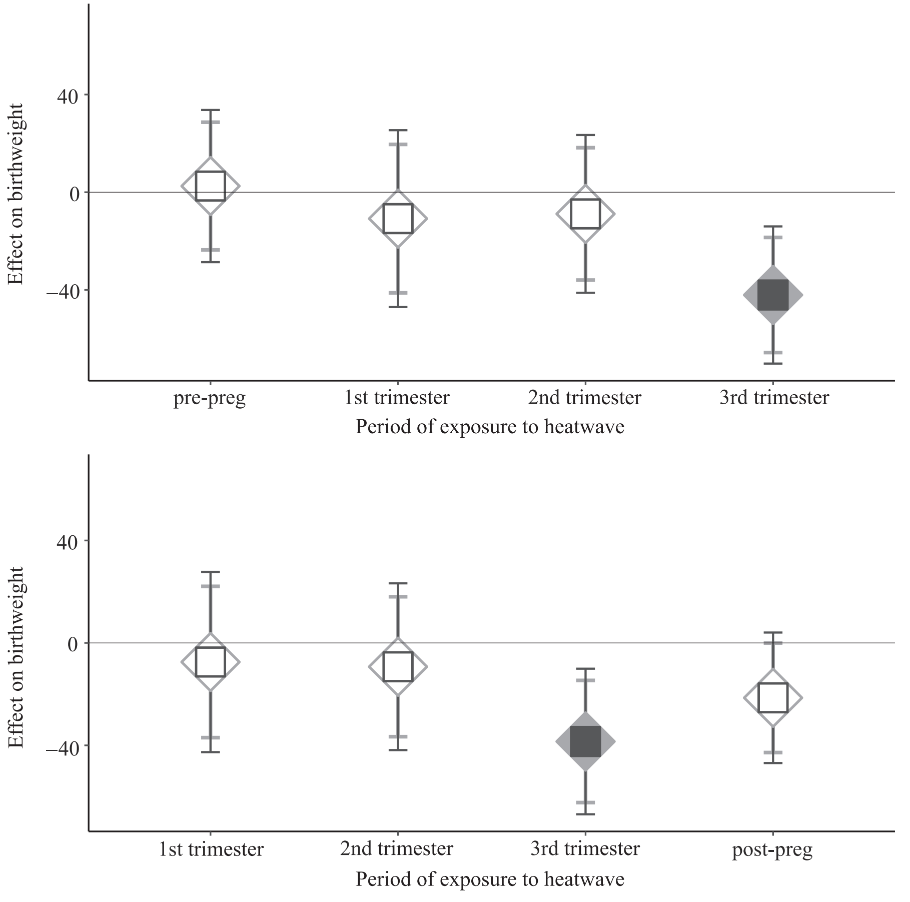
result of heatwave exposure (Figure 7). The results show that the effect of heatwave on birthweight is mainly concentrated among male births and babies born into families where the mothers have no to little formal education (i.e., no education and primary education). However, the effect of heatwave on birthweight is not moderated by paternal education and type of residence: babies of high-educated fathers are as disadvantaged as babies of low-educated fathers, and babies living in urban areas are as disadvantaged as babies living in rural areas. These findings have two important implications. First, they show that male babies are highly vulnerable to heatwave exposure. They also show the importance of female education in shielding from the negative health consequences of heatwave shocks.

Sensitivity analyses

I now move to two potential sources of selectivity that may bias the effect of heatwave on birthweight: (1) an increase in miscarriage resulting from heatwave exposure and (2) a change in fertility patterns as a response to heatwave.

First, women exposed to heatwave during pregnancy may have been more likely to miscarry. Prior research finds that maternal exposure to climate extremes increases pregnancy loss (Davenport, Dorélien, and Grace 2020). This means that if a weaker fetus with potentially low birthweight is more likely to die in utero due to heatwave, then the results would be based

FIGURE 8 Effect of heatwave on birthweight by period of exposure



NOTES: Obtained from parameter estimates in Table A6. Dots indicate parameter estimates; light and dark gray vertical bars are the 90 and 95 percent confidence intervals, respectively; and dots colored light and dark gray indicate estimates significant at the 10 and 5 percent levels, respectively. Exposure to heatwave is calculated over the 40-week interval starting from the month of conception and estimated as the effect of exposure to heatwave during the trimester prior to conception, during the first, second, and third trimesters of pregnancy, and during the trimester after birth. Data are weighted to make the results representative of babies living in these 11 countries in SSA, and standard errors are clustered by region.
SOURCE: As for Table 1.

on a selected sample of presumably stronger fetuses. It is worth noting that this will likely underestimate the true effect of in utero exposure to heatwave on birthweight. Therefore, selection bias from selective miscarriage would not undermine the main results of this analysis.

To rule out that selective miscarriage introduces bias, I implement an indirect strategy based on the reasoning that an increase in the proportion of miscarriages resulting from heatwave exposure will likely cause a decline in multiple birth rates if the weak fetus dies. I, therefore, assess whether heatwave reduces the probability of multiple births (e.g., twins, triplets, etc.) by estimating Equation (1) with the dependent variable of multiple births.[10] The analysis finds that heatwave does not reduce the probability of multiple births thus suggesting that selective miscarriage is not confounding my results (see Table A5 in the online Appendix for results).

Finally, fertility patterns may also have changed in ways that alter the composition of babies born. If, for example, fertility decreased among better-educated women as a response to heatwave, the increase in low birthweight may be due to the selective reduction of the population. The literature finds that by worsening reproductive health, high-temperatures reduce fertility (Barreca, Deschênes, and Guldi 2018). If this were the case, we would see an effect of heatwave prior to conception on birthweight. It is again worth noting that selective fertility will likely underestimate the true effect of in utero exposure to heatwave on birthweight.

To assess the possibility of a change in fertility patterns due to heatwave, I include a lead and a lag variable of heatwave and examine whether heatwave before conception and after pregnancy affect birth outcomes. A null effect of lagged heatwave would rule out endogenous selection effects, which could explain the estimates if mothers with a lower propensity to give birth to low-weight babies (e.g., better-educated mothers) show reduced fertility rates as a result of heatwave. A null effect of leaded heatwave would also rule out potential selection effects that operate through anticipation of future heatwave. Figure 8 plots the effects of heatwave on birthweight, gestational age, and uterine growth across the five periods of exposure—trimester prior to conception, first, second, and third trimesters of gestation, and trimester after birth—and the 90 and 95 percent confidence intervals (Table A6 in the online Appendix presents parameter estimates, standard errors, and significance tests). Results are unaffected by the inclusion of these variables, and there is no evidence of lagged (top plot) and lead (bottom plot) effects of heatwave.

Discussion and conclusions

Demographic and public health research has revealed that in utero environmental shocks can affect children's health at birth. This study builds on existing scholarship by providing evidence on the causal impact of in utero exposure to heatwave on birthweight in 11 SSA countries—an important subject of inquiry given that the frequency, intensity, and duration of heat-related events are expected to increase with global warming through the 21st century (IPCC 2019). Low birthweight as a consequence of heatwaves could have important ramifications for the health and development of newborns as children and adults. It could cause poor health and low educational attainment—with dramatic societal consequences for generations to come.

The analysis makes three main contributions. First, the analysis showed a significant decline in birthweight of 41.8 grams among babies exposed to heatwave during the third trimester of gestation. I further find that heatwave exposure does not simply reduce birthweight within a normal range but increases the proportion of low-weight births to such an extent that will likely cause health and developmental problems later in life. I also provide evidence that estimates are not driven by selection bias. Specifically, I show that exposure before conception and after birth does not affect birth outcomes, and that it is precisely exposure during the third trimester of pregnancy that affects birth outcomes.

Is a decline of birthweight by 41.8 grams substantively relevant? My assessment is that it is. I use previous research estimating the effects of other environmental shocks and major policy interventions as benchmarks against which to compare my findings. For example, Torche (2011) finds an effect of about 50 grams due to exposure to a major earthquake during the first trimester of gestation, and Mansour and Rees (2012) find an effect of about 5 grams among educated mothers due to the al-Aqsa intifada in Palestine. Andalón et al. (2016) find an effect of 4.1 grams due to exposure to moderate heatwaves during the third trimester of pregnancy. Torche and Shwed (2015) find an effect of approximately 15 grams resulting from the Israel–Hezbollah war in the first and second trimesters of gestation, and Foureaux Koppensteiner and Manacorda (2016) find that one standard deviation rise in the homicide rate during the first trimester of pregnancy leads to a reduction in birthweight of around 2 grams. Hoynes et al. (2011) find an effect of the Supplemental Nutrition Program for Women, Infants, and Children on birth weight of 2.5 grams among disadvantaged women, and Almond et al. (2011) find an effect of the Food Stamp Program on birth weight of approximately 2.5 grams for whites and four grams for blacks. The effect of a decline in birthweight by 41.8 grams due to exposure in the third trimester appears substantively relevant.

These results accord with previous findings of the effect of heatwaves on birthweight which show that weight at birth is negatively affected by exposure to moderate heatwaves during the third trimester of pregnancy (Andalón et al. 2016). My analysis contributes to this important line of work but extends it by comprehensively examining the timing and mechanisms that underpin the effects of heatwave on birthweight. I show that heatwave exposure in the third trimester of pregnancy affects birthweight through reduced gestational age. I find that increased prematurity, rather than intrauterine growth retardation, explains the pronounced effect on low birthweight.

The effect of heatwave was concentrated in the third trimester and largely mediated by reduced gestational age which suggests that the effect of heatwaves is driven by a stress reaction among pregnant women, corroborating previous studies that found that heat stress during pregnancy leads to lower birthweight (Grace et al. 2021; Davenport, Dorélien, and Grace 2020; Grace et al. 2015; Deschênes, Greenstone, and Guryan 2009). I find that the effect of heat stress is larger in magnitude than what was previously suggested, perhaps because previous studies focus on hot days, whereas I investigated the effect of heatwaves on birthweight. Heatwaves are periods of persistently hot days and represent a more intense and prolonged exposure compared to individual hot days. Consequently, the impact of heatwaves on birthweight may be more detrimental than the effect of isolated hot days, which could explain why the estimates in these studies are smaller in magnitude. This interpretation is supported by my results in supplementary analyses that the effect on birthweight losses increases with the duration of heatwaves as a continuous variable.

Third, I assess differential vulnerabilities to heatwave across subgroups of the population. I find that the effects of heatwave on birthweight are concentrated among male babies and babies born to less-educated mothers. Maternal education, therefore, is an important determinant of climate-related vulnerabilities, as also shown by Dimitrova and Muttarak (2020). This finding speaks to an ongoing debate about climate change adaptation which has highlighted the central role of female education in reducing vulnerability to weather shocks and increasing the propensity to prepare against natural disasters (Muttarak and Lutz 2014; Lutz, Muttarak, and Striessnig 2014; Hoffmann and Muttarak 2017). This finding also lends support to recent evidence on the effects of hot days on birth outcomes (Conte Keivabu and Cozzani 2022) where the negative effects of heat on birth outcomes are found to be moderated by socioeconomic conditions. Interestingly, I do not find evidence that the type of residence protects children from the negative health consequences of heatwave exposure. The future demographic scholarship would benefit—not least for its obvious policy implications—from a systematic analysis of the conditions under which socioeconomic characteristics can dampen the effect of weather shocks on demographic outcomes.

This study also faces limitations that invite further research. First, while I opted for a definition of heatwave that is based on temperature alone because it is the most direct measure of heat, it would be an important avenue for future research to assess how temperature interacts with other metrics such as wind speed, solar radiation, and humidity. For example, humidity, particularly in regions with consistently warm and humid climates, could further exacerbate the health consequences of higher temperatures by impeding the human body's ability to dissipate heat through sweating (Gosling et al. 2009; Im, Pal, and Eltahir 2017). If the impact of heatwave on health operates through stress, disregarding the role of humidity could result in underestimating the effect of heatwave on birth outcomes. Future research interested in the effect of heat stress on birth outcomes could, for example, use nuanced heat metrics such as the heat index or the Wet Bulb Globe Temperature.

Second, this work investigates differential vulnerability to heatwave but it does not directly capture the local adaptations and vulnerabilities specific to different communities. For example, factors such as access to cooling infrastructure, availability of water resources, cultural practices, and livelihood patterns play a significant role in determining how populations cope with and are affected by heatwaves. It is the task of future work to assess how local contextual factors may affect the interplay between exposure to heatwaves and vulnerability within diverse populations.

Third, in this work, I focused on birth outcomes. Birthweight is an important determinant of health and well-being later in life, but it only captures children's health status at birth. Whether these findings also extend to health and well-being later in life remains to be tested. If parents compensate for early-life disadvantages, prenatal exposure to heatwave might not lead to poorer health and well-being over the life course. However, prior research shows that while highly educated mothers tend to compensate for early-life disadvantages, less-educated mothers reinforce early-life disadvantages (Hsin 2012). This would suggest that in utero exposure to heatwave could exacerbate health and socioeconomic inequalities over the life course. Future research should therefore investigate how in utero exposure to heatwave shapes health and socioeconomic trajectories.

Overall, the results from my analyses are relevant to practitioners and policymakers who design policies to reduce the negative impacts of climate change. First, these findings urge us to carefully consider conditions prior to birth that are known to have important consequences for health and socioeconomic inequalities. Second, it is crucial to invest in maternal education to enhance women's abilities to mitigate the consequences of exposure to heatwaves during pregnancy. Ultimately, this analysis showed how a cutting-edge measure of climate extremes can be combined with georeferenced DHS data to better understand the linkages between climate change and population characteristics. Given that climate extremes will likely increase in the coming decades, there is an urgent need for deepening our understanding of the relationship between climatic processes and population health beyond the scope of this study.

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Notes

1 This approach is consistent with that of other high-quality sources, including the DHS program's own geospatial dataset and IPUMS-DHS.

2 ERA5 data are available on the Copernicus Climate Change Service (C3S) Climate Data Store: https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form

3 Two main reasons motivate the decision to make use of the ERA5 dataset over other reanalysis datasets including MERRA2 (National Oceanic Atmospheric Administration's Modern-Era Retrospective Analysis for Research and Applications, Version 2) and JRA-55 (Japanese Meteorological Agency's 55-year reanalysis). First, ERA5 demonstrates greatly reduced bias in surface air temperature (Betts, Chan, and Desjardins 2019; Graham, Hudson, and Maturilli 2019; Mahto and Mishra 2019), which is the main climate parameter that is used in my work. Second, I prefer ERA5 over MERRA2 and JRA-5 because it has a higher spatial resolution. MERRA2 and JRA-55 have a spatial resolution of 0.625×0.5 and 1.25×1.25 in longitude and latitude, respectively, whereas ERA5 has a spatial resolution of 0.25×0.25. The higher spatial resolution of ERA5 enables me to capture variation over space that coarser measures are not able to capture.

4 Previous DHS collected the day of birth only for living children under the age of 5 who live in the household, which means that children who died and who very likely had lower birthweight were excluded.

5 As a supplementary analysis, I estimate the analyses on the full sample (including both migrants and non-migrants) and find that results are quantitatively the same.

6 I estimate Equation (1) where the dependent variable is a binary variable equal to 1 if birthweight was missing and 0 otherwise—the same set of covariates, except for the dummy variable on the source of birthweight information, are included.

7 Birthweight is recorded based on mother's recall or a health card. To account for the possibility that the mother's recall may be influenced by other factors and may not be completely accurate, the models include a dummy variable indicating whether the birthweight information was from mother's recall or from a health card.

8 These fixed effects also control for differences across countries.

9 These weights are calculated as the ratio between the population of the country in the year of the survey and the sample size of the survey in which the baby appears.

10 The same set of covariates, except for child's sex and the dummy variable on the source of birthweight information, are included. To avoid counting multiple births more than once, I restrict the sample to all single births and one of the multiple births.

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