## Title

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**Permalink**
https://escholarship.org/uc/item/3nm3g55v

**Journal**
Paediatric and Perinatal Epidemiology, 36(1)

**ISSN**
0269-5022

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**Publication Date**
2022

**DOI**
10.1111/ppe.12834

Peer reviewed

Received: 8 March 2021 | Revised: 21 October 2021 | Accepted: 24 October 2021
DOI: 10.1111/ppe.12834

SPECIAL ISSUE ARTICLE

Paediatric and Perinatal Epidemiology
WILEY

# Extreme heat and its association with social disparities in the risk of spontaneous preterm birth

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**Funding information**
Robert and Patricia Switzer Foundation; Energy & Resources Group at the University of California, Berkeley; Alex Farrell Memorial Graduate Fellowship; Environmental Protection Agency, Grant/Award Number: 91744701

A commentary based on this article appears on pages 23-25

## Abstract

**Background:** Climate change is increasing the frequency and intensity of heatwaves. Prior studies associate high temperature with preterm birth.

**Objectives:** We tested the hypotheses that acute exposure to extreme heat was associated with higher risk of live spontaneous preterm birth (≥20 and <37 completed weeks), and that risks were higher among people of colour and neighbourhoods with heat-trapping landcover or concentrated racialised economic disadvantage.

**Methods:** We conducted a retrospective cohort study of people giving birth between 2007 and 2011 in Harris County, Texas (Houston metropolitan area) (*n* = 198,013). Exposures were daily ambient apparent temperature ($AT_{max}$ in 5°C increments) and dry-bulb temperatures ($T_{max}$ and $T_{min}$ >historical [1971–2000] summertime 99th percentile) up to a week prior for each day of pregnancy. Survival analysis controlled for individual-level risk factors, secular and seasonal trends. We considered race/ethnicity, heat-trapping neighbourhood landcover and Index of Concentration at the Extremes as effect modifiers.

**Results:** The frequency of preterm birth was 10.3%. A quarter (26.8%) of people were exposed to $AT_{max}$ ≥40°C, and 22.8% were exposed to $T_{max}$ and $T_{min}$ >99th percentile while at risk. The preterm birth rate among the exposed was 8.9%. In multivariable models, the risk of preterm birth was 15% higher following extremely hot days (hazard ratio [HR] 1.15 (95% confidence interval [CI] 1.01, 1.30) for $AT_{max}$ ≥40°C vs. <20°C; HR 1.15 (95% CI 1.02, 1.28) for $T_{max}$ and $T_{min}$ >99th percentile). Censoring at earlier gestational ages suggested stronger associations earlier in pregnancy. The risk difference associated with extreme heat was higher in neighbourhoods of concentrated racialised economic disadvantage.

**Conclusions:** Ambient heat was associated with spontaneous preterm birth, with stronger associations earlier in pregnancy and in racially and economically disadvantaged neighbourhoods, suggesting climate change may worsen existing social inequities in preterm birth rates.

KEYWORDS
birth outcomes, climate change, environmental justice, heatwave, segregation, temperature

## 1 | BACKGROUND

Preterm birth is a major public health concern, with an estimated 15 million preterm births each year.[1] Preterm birth is a primary cause of infant mortality and can lead to later health problems.[2–4] Several studies indicate high temperatures increase preterm birth risk,[5,6] although others have found no association[7–10] or a protective effect.[11] The possibility that extreme heat causes preterm birth is worrisome given that heatwaves are becoming more frequent due to climate change.[12]

How heat triggers preterm birth is not well understood. Laboratory studies with ewes and pregnant people suggest acute heat stress causes uterine contractility and the release of labour-inducing hormones.[13,14] Pregnancy increases the risk of heat stress because weight gain and foetal growth raise the basal metabolic rate[15] and body fat impedes heat loss.[16]

In the United States, Black, Native American and Latinx people are at greater risk of preterm birth than Whites,[17] and several studies show people of colour experience greater heat-related preterm births.[18–20] Racial and ethnic differences in vulnerability to heat could result from inequalities in occupational setting, housing, pre-existing health conditions and other manifestations of social, economic and political marginalisation resulting from structural racism.[21–23] In the U.S. metropolitan areas, people of colour are more likely to live in segregated neighbourhoods with fewer trees and more heat-trapping impervious surfaces such as asphalt and concrete, which contribute to localised heat-island effects.[24] Together, this suggests heatwaves and inequalities in neighbourhood land cover could worsen racial/ethnic disparities in preterm birth.

We sought to examine the environmental justice implications of extreme heat using birth records from Harris County, Texas, the United States, during a time period (2007–2011) that included a landmark heatwave. We conducted a retrospective cohort study to investigate whether acute exposure to heat was associated with spontaneous preterm birth, and whether people of colour or residents of neighbourhoods with heat-trapping land cover or racialised economic disadvantage were at greater risk at the same level of heat exposure. Harris County includes the city of Houston, one of the five most populous U.S. metropolitan areas. Although this study looked at extreme heat over a five year period, we note that Texas experienced its hottest summer on record in 2011 with average temperatures over 2.7°C above the long-term average.[25]

## 2 | METHODS

### 2.1 | Cohort selection

Geocoded birth records were obtained from the Texas Department of State Health Services. Births were eligible for inclusion if they were not an induced labour and had an obstetric estimate of gestational age.

Exclusion criteria and the construction of the sample population are illustrated in Figure 1. Births with improbable combinations of gestational age and birthweight were excluded using cut points from a national reference corresponding roughly to the 1st and 99th percentile of gestational age for each 125 g birthweight interval.[26] Births conceived prior to 14 August 2006 or after 6 March 2011 were excluded in order to control for ‘truncation’ bias.[10,27] Truncation bias can arise in retrospective observational studies that restrict on the date of birth due to the over-representation of longer pregnancy at the beginning and shorter pregnancies at the end of the study period.[27] Restricting on conception rather than birth date ensures inclusion of all people who were pregnant at the same time regardless of when they gave birth. Excluded births were disproportionately White, slightly higher socioeconomic status, and older; they also had a higher rate of preterm and low weight births due to the inclusion of multiples (Table S1). Since the data did not include identifiers, repeat pregnancies to the same person were considered as independent observations.

### Synopsis

**Study question**

Does exposure to extreme heat during pregnancy increase the risk of spontaneous preterm birth, and are women of colour at greater risk?

**What is already known?**

In some but not all prior studies, exposure to heat has been associated with increased risk of preterm birth. Most studies were conducted in temperate climates and did not consider differential vulnerability with respect to race/ethnicity, neighbourhood land cover characteristics or segregation.

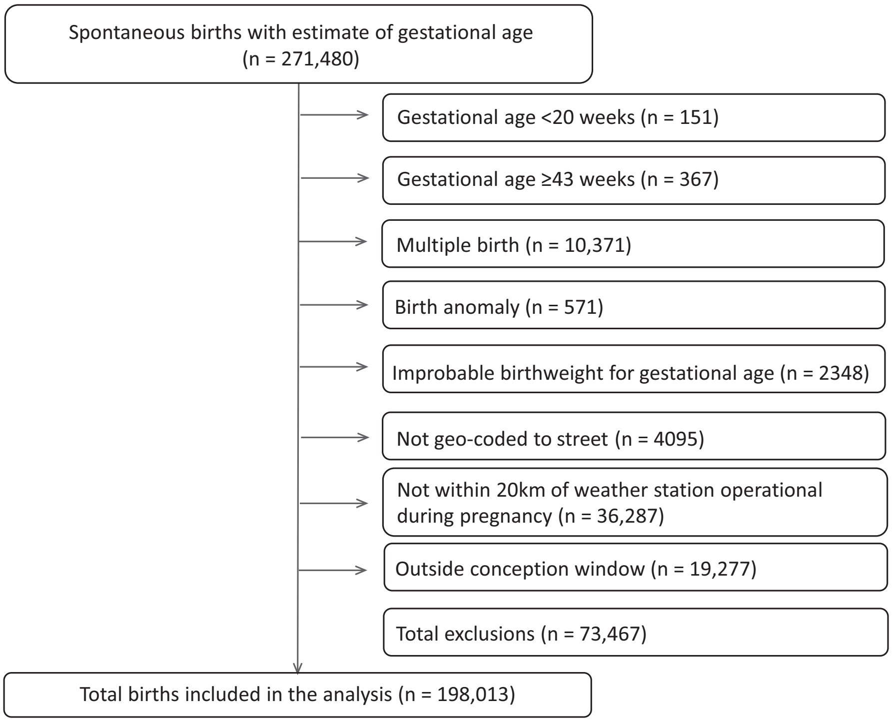
**What this study adds?**

In a humid subtropical climate, we find an association between acute ambient heat and preterm birth that is stronger earlier in pregnancy. We find evidence of positive interaction with racialised economic segregation, suggesting extreme heat may worsen existing social disparities in preterm birth rates.

### 2.2 | Exposure

We created a time-varying exposure where temperature varied by day at risk, starting at day 140 (20 completed weeks) and ending at birth or day 258 (36 weeks and 6 days), whichever came first. Births were linked to temperature records from the nearest of ten weather stations. We characterised heat in two ways. We considered maximum daily apparent temperature ($AT_{max}$ in 5°C increments) for up to 7 days prior to the gestational day at risk because AT—a

**FIGURE 1** Flow diagram of study population assembly from 2007 to 2011 Harris County, TX birth records



combined measure of heat and humidity—better approximates perceptions of heat than dry-bulb temperature, and previous studies indicate that exposure over this time frame can increase the risk of preterm birth.[18,28–30] We chose to model $AT_{max}$ in 5°C increments *a priori* to allow for nonlinearity in the relationship, ease of interpretability, and because we did not have an *a priori* hypothesis about what threshold temperature may trigger birth. We also considered daily dry-bulb minimum ($T_{min}$) and maximum ($T_{max}$) air temperatures that both exceeded their respective 99th percentile of historical (1971–2000) summertime June, July, August (JJA) records. We chose this measure based on prior research showing the importance of warm nights with respect to mortality and to facilitate comparisons across climates. Dry-bulb temperatures were used because historical records of AT were not readily available.

Weather data were downloaded from the National Oceanic and Atmospheric Administration Climate Data Online portal (http://www.ncdc.noaa.gov/cdo-web/), observations flagged by NOAA as suspect or erroneous were removed (<3%). Daily $AT_{max}$ was estimated from hourly data using the day's maximum dry-bulb temperature and mean vapour pressure using the formula in Steadman (1984).[31] We calculated historical 99th percentiles for JJA daily minimum (25.6°C) and maximum (37.2°C) air temperatures using data from two central locations in the county operational throughout the thirty years.

The U.S. census tracts were used as a proxy for neighbourhood of residence. Tracts are relatively stable, generally contiguous geographic areas containing roughly 1200–8000 residents. The per cent of a tract that was covered by impervious surfaces and tree canopy was estimated from the 2011 National Land Cover Database[32] using TIGER/Line files (https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.html) and ArcMap 10.3 (ESRI, Redlands, CA). The per cent of each census tract covered in water was obtained from the TIGER/Line files. High heat risk tracts were defined as those with none of their area covered in water, less than 5% of their area covered in tree canopy, and more than 60% of their area covered in impervious surfaces.

The Index of Concentration at the Extremes (ICE) was calculated using 5 year (2007–11) tract-level population estimates from the American Community Survey (https://www.census.gov/programs-surveys/acs/).[33] ICE measures the extent to which disadvantaged and privileged populations are concentrated in an area and ranges from −1 (entire tract population belongs to the most disadvantaged group) to 1 (entire tract population belongs to the most privileged group). We defined the disadvantaged group as people of colour with an annual household income <$25,000 and the advantaged group as Non-Hispanic White people with an annual household income >$100,000.

## 2.3 | Outcomes

We used the obstetrician's estimate of gestational age in weeks to define spontaneous preterm birth (≥20 and <37 completed weeks). Because we lacked information on preterm labour, preterm prelabour rupture of membranes or cervical incompetence, we relied on restriction to non-induced labours in order to exclude non-spontaneous, medically indicated preterm deliveries.

## 2.4 | Statistical analysis

We controlled for season of birth and secular time as these are likely confounders associated with both heat and underlying risk of spontaneous preterm birth. In order to increase the precision of our estimates, we additionally controlled for known risk factors of preterm birth that were unlikely to be associated with heat. Many studies of the relationship between temperature and health control for ambient ozone and particulate matter as confounders. We considered these air pollutants as causal intermediates because sunlight and high temperatures promote their formation from precursor molecules in the atmosphere.[34–36] A directed acyclic graph (DAG) representing the hypothesised exposure-outcome relationship is provided in Figure S1.

We examined descriptive statistics for all variables and compared crude spontaneous preterm birth rates by risk factors defined *a priori* based on previous studies. We then estimated the hazard of spontaneous preterm birth using Cox models with gestational age in days as the time axes. This accounts for underlying changes in the distribution of gestational ages at risk by estimating the likelihood of birth versus staying pregnant among pregnancies at the same stage. The reported date of last menstrual period was used as the conception date when it occurred during week one of gestation as estimated by the obstetrician; otherwise, a random day of week one was chosen. Pregnancies entered the study at 20 completed weeks (140 days) and were censored at 37 completed weeks (259 days) when they were no longer at risk. The Efron method was used to handle ties.[37]

The first set of models included one temperature variable, season of birth and the number of days since 1 January 2007 to control for seasonal and secular trends. We considered lagged temperature variables up to one week as well as mean $AT_{max}$ over the three days ($lag_1$-$lag_3$) and seven days ($lag_1$-$lag_7$) prior to the gestational day at risk.

The second set of models included the following time-invariant individual risk factors as covariates to improve precision: infant sex (male or female), adequacy of prenatal care (inadequate, intermediate, adequate or adequate plus),[38] maternal age (in 5 years increments), high-risk pregnancy status based on presence of gestational or pre-pregnancy diabetes or hypertension, preeclampsia or eclampsia (yes/no), race/ethnicity as a proxy for racial treatment in a racist society (Hispanic/Latinx, non-Hispanic White, non-Hispanic Black, non-Hispanic Asian/Pacific Islander, or other/multiple/unknown), nativity (foreign- vs. U.S.-born), education (<high school (HS), HS graduate or equivalent, or >HS), pre-pregnancy body mass index (underweight [$<18.5$ kg/m$^2$], normal [18.5–25 kg/m$^2$], or overweight/obese [$\geq 25$ kg/m$^2$]), smoking during or within three months prior to pregnancy (yes/no), and expected primary source of payment (private insurance vs. Medicaid/self-pay/other).

The third set of models added interaction terms between temperature and race/ethnicity, neighbourhood land cover, or ICE. Small sample sizes precluded us from examining other racial and ethnic groups. Evidence for interaction was assessed on the multiplicative and additive scales.[39]

We calculated the population attributable fraction associated with $AT_{max}$ ≥40°C using the following formula[40]:

$$PAF_i = p_i \times \frac{(HR - 1)}{HR}$$

where $p$ is the proportion of cases of spontaneous preterm birth exposed to heat while at risk during the study period for racial/ethnic group $i$, and HR is the adjusted hazard ratio. Since this formula requires a binary exposure, we ran an alternate version of our final model that categorised $AT_{max}$ as ≥40°C versus <40°C.

Data cleaning was performed in R, and statistical analysis was performed in SAS 9.4 (SAS Insttitute, Cary, NC).

## 2.5 | Missing data

Prenatal care information was missing for 6.7% of people. For all other variables, <1% of observations had missing data (Table 1).

## 2.6 | Sensitivity analysis

We evaluated the assumption of constant relative hazards by censoring at earlier gestational ages (28, 32 and 36 weeks). We calculated the E-value using an online calculator.[41,42] To examine the impact of missing data, we include a sensitivity analysis of the main model using multiple imputation with 20 imputations. To assess potential bias due to the exclusion of births more than 20 km from a weather station, we conducted a sensitivity analysis in which we re-assigned $AT_{max}$ using modelled 4 × 4 km gridded estimates of dry-bulb and dew point temperatures from PRISM.[43]

## 2.7 | Ethics approval

Study protocols were approved by the institutional review boards at Texas Department of State Health Services (#13-047) and the University of California, Berkeley (#2013-07–5481).

## 3 | RESULTS

The final sample population included 198,013 births, 10.3% of which were preterm (Table 1). Rates of conception increased from June to December and then decreased (Figure S2). Crude rates of preterm birth were higher for risk factors identified *a priori*: male infants, birth parents that were U.S.-born, smokers, under age 20 or over age 35, underweight, obese, African American had inadequate or more than adequate prenatal care and pregnancy complications. The per cent of area covered in tree canopy ranged varied across tracts from 0% to 73%; the per cent covered in impervious surface varied from 3% to 93%. Roughly, 10% of birth parents lived in tracts defined as high heat risk (Table 1), with the rate being higher for Hispanic/Latinx (11.2%), Black (9.4%) and Asian/Pacific Islanders (9.8%) than Whites (4.4%, data not shown).

Roughly, a quarter of birth parents were exposed to at least one day of extreme heat while at risk of preterm delivery (Table 1). Average $AT_{max,}$ the week prior to birth, was slightly higher among

**TABLE 1** Characteristics of the sample population of Harris County, TX births, 2007–11 (*N* = 198,013), stratified by preterm birth status. HS =high (secondary) school[a]

| | *N* (%), term births | *N* (%), preterm births |
|---|---|---|
| Infant sex | | |
| Male | 90,094 (50.7%) | 10,795 (52.8%) |
| Female | 87,456 (49.3%) | 9668 (47.2%) |
| Birth parent age (years) | | |
| <20 | 20,921 (11.8%) | 2587 (12.6%) |
| 20–24 | 44,353 (25.0%) | 5030 (24.6%) |
| 25–29 | 48,965 (27.6%) | 5271 (25.8%) |
| 30–34 | 39,689 (22.4%) | 4347 (21.2%) |
| 35–40 | 19,429 (10.9%) | 2501 (12.2%) |
| ≥40 | 4,192 (2.4%) | 727 (3.6%) |
| Missing | 1 (<0.1%) | 0 (0%) |
| Race/ethnicity | | |
| Hispanic/Latinx | 99,356 (56.0%) | 10,109 (49.4%) |
| White | 34,562 (19.5%) | 3846 (18.8%) |
| Black | 30,997 (17.5%) | 5364 (26.2%) |
| Asian/Pacific Islander | 11,016 (6.2%) | 996 (4.9%) |
| Native American | 185 (0.1%) | 21 (0.1%) |
| Other/multiple | 1200 (0.7%) | 95 (0.5%) |
| Missing | 234 (0.1%) | 32 (0.2%) |
| Nativity | | |
| Foreign-born | 82,042 (46.%) | 7423 (35.3%) |
| US-born | 95,428 (53.7%) | 13,018 (63.6%) |
| Missing | 80 (<0.1%) | 22 (0.1%) |
| Birth parent's education | | |
| <HS | 66,362 (37.4%) | 7291 (35.6%) |
| HS graduate or equivalent | 39,643 (22.3%) | 4960 (24.2%) |
| >HS | 71,351 (40.2%) | 8169 (39.9%) |
| Missing | 194 (0.1%) | 43 (0.2%) |
| Insurance | | |
| Private | 54,822 (30.9%) | 6198 (30.3%) |
| Medicaid | 84,867 (47.8%) | 10,089 (49.3%) |
| Self-pay/other | 36,921 (20.8%) | 4050 (19.8%) |
| Missing | 940 (0.5%) | 126 (0.6%) |
| High-risk pregnancy | | |
| Yes | 13,340 (7.5%) | 3711 (18.1%) |
| No | 164,210 (92.5%) | 16,752 (81.9%) |
| Adequacy of prenatal care | | |
| Inadequate | 53,260 (30.3%) | 6383 (31.2%) |
| Intermediate | 22,471 (12.7%) | 1054 (5.2%) |
| Adequate | 53,875 (30.3%) | 2602 (12.7%) |
| Adequate plus | 36,676 (20.7%) | 8460 (41.3%) |
| Missing | 11,268 (6.4%) | 1,964 (9.6%) |
| Pre-pregnancy body mass index (BMI) | | |
| Underweight | 8990 (5.1%) | 1341 (6.6%) |
| Healthy weight | 84,0480 (47.3%) | 9046 (44.2%) |
| Overweight | 46,721 (26.3%) | 5146 (25.1%) |
| Obese | 37,799 (21.3%) | 4930 (24.1%) |
| Smoking | | |
| No | 171,685 (96.7%) | 19,425 (94.9%) |
| Yes | 5619 (3.2%) | 1005 (4.9%) |
| Missing | 246 (0.1%) | 33 (0.2%) |
| Year | | |
| 2007 | 24,729 (13.9%) | 3280 (16.0%) |
| 2008 | 38,994 (22.0%) | 4430 (21.6%) |
| 2009 | 41,175 (23.2%) | 4788 (23.4%) |
| 2010 | 38,127 (21.5%) | 4465 (21.8%) |
| 2011 | 34,525 (19.4%) | 3500 (17.1%) |
| Season | | |
| Spring (MAM) | 37,617 (21.2%) | 4836 (23.6%) |
| Summer (JJA) | 49,822 (28.1%) | 5881 (28.7%) |
| Fall (SON) | 50,809 (28.6%) | 5301 (25.9%) |
| Winter (DJF) | 39,302 (22.1%) | 4445 (21.7%) |
| Gestational age (completed weeks) | | |
| Extremely preterm (20 – 27) | -- | 837 (4.1%) |
| Very preterm (28 – 31) | -- | 1806 (8.8%) |
| Moderately preterm (32 – 36) | -- | 17,820 (87.1%) |
| Early term (37 – 38) | 68,754 (38.7%) | -- |
| Term (39 – 42) | 108,796 (61.3%) | -- |
| Birthweight (g) | | |
| Very low (<1,500) | 53 (0.0%) | 2157 (10.5%) |
| Low (1,500–2,500) | 4402 (2.5%) | 7629 (37.3%) |
| Not low (≥2,500) | 173,095 (97.5%) | 10,677 (52.2%) |
| Exposed to extreme heat at least once while at risk | | |
| $AT_{max}$ ≥40°C | 48,407 (27.3%) | 4712 (23.0%) |
| $T_{min}$ & $T_{max}$ >JJA 99th percentile | 41,162 (23.2%) | 4031 (19.7%) |
| Heat-trapping neighbourhood landcover[b] | | |
| Yes | 17,009 (9.6%) | 1782 (8.7%) |
| No | 160,541 (90.4%) | 18,681 (91.3%) |
| Index of Concentration at the Extremes | | |
| Quintile 1 (most disadvantaged) | 52,154 (29.4%) | 6536 (31.9%) |
| Quintile 2 | 45,408 (25.6%) | 5161 (25.2%) |
| Quintile 3 | 30,317 (17.1%) | 3444 (16.8%) |
| Quintile 4 | 26,184 (14.7%) | 2868 (14.0%) |
| Quintile 5 (most privileged) | 21,949 (12.4%) | 2254 (11.0%) |
| Missing | 1,538 (0.9%) | 200 (1.0%) |

[a] Percentages may not sum to 100% due to rounding.

[b] Defined as residence within a census tract with no water, <5% of its area covered in tree canopy, and >60% of its area covered in impervious surfaces.

spontaneous preterm as compared to term births (Table S2). The per cent of births exposed to $T_{max}$ and $T_{min}$ >JJA 99th percentile, the day prior to birth, was slightly higher among spontaneous preterm as compared to term births (Table S3).

Hazard ratios controlling for season and secular trend suggested one-day lagged temperature had the strongest association with spontaneous preterm birth (Figure 2), and for that reason, one-day lags

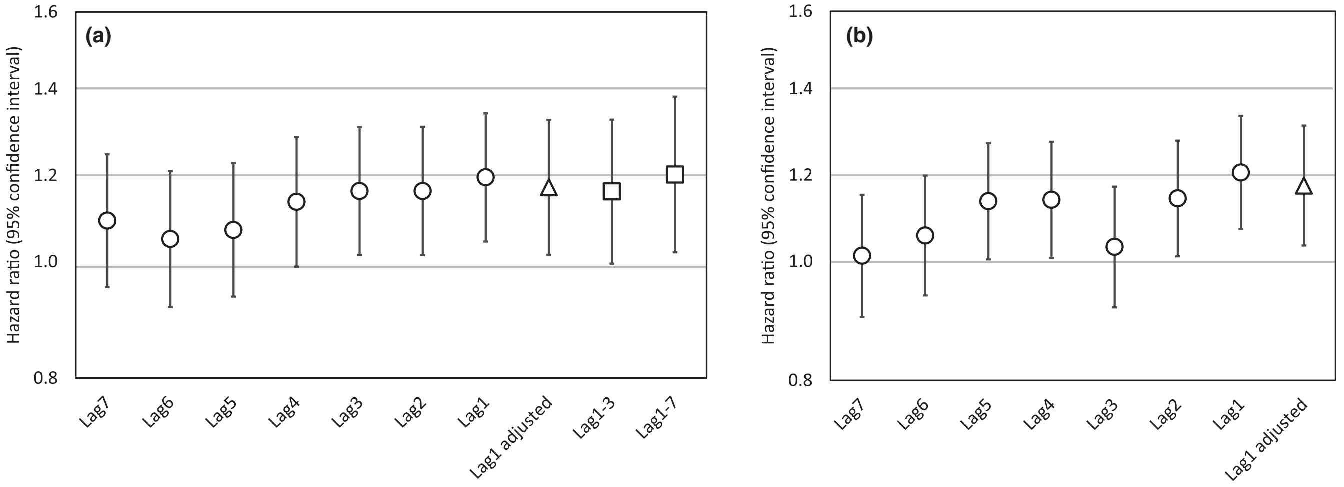


**FIGURE 2** HRs for the risk of preterm birth following unusually hot days defined as (A) $AT_{max}$ ≥40°C (vs. <20°C) and (B) days with both $T_{max}$ and $T_{min}$ >the 99th percentile of historical (1971–2000) summertime (JJA) observations (complete case analysis $N = 183{,}414$). Circles, triangles and squares indicate HRs. Whiskers indicate 95% CIs. $Lag_1$ indicates one day prior to the gestational day at risk, $lag_2$ two days prior, etc. $Lag_{1\text{-}3}$ and $lag_{1\text{-}7}$ are averages over the three and seven days prior, respectively. All models control for season and secular trend. Adjusted models additionally control for infant sex and maternal age, prenatal care, high-risk status (diabetes/hypertension), race/ethnicity, nativity, education, body mass index, smoking and insurance. HR, hazard ratio; JJA, June, July, August

**TABLE 2** Hazard ratios and 95% CIs for the association between extreme heat and the risk of preterm birth when censoring at earlier gestational ages

| Temperature the day prior (lag 1) | Time of censoring | | | |
|---|---|---|---|---|
| $AT_{max}$ (ref: <20°C) | 37 weeks | 36 weeks | 32 weeks | 28 weeks |
| ≥40°C | 1.15 (1.01, 1.31) | 1.26 (1.07, 1.50) | 1.75 (1.15, 2.68) | 3.15 (1.39, 7.10) |
| 35–40°C | 1.05 (0.98 1.12) | 1.12 (1.03, 1.22) | 1.87 (1.56, 2.24) | 3.18 (2.27, 4.45) |
| 30–35°C | 1.01 (0.95, 1.07) | 1.08 (1.00, 1.17) | 1.69 (1.43, 1.99) | 2.37 (1.74, 3.21) |
| 25–30°C | 0.99 (0.94, 1.04) | 0.99 (0.93, 1.06) | 1.14 (0.98, 1.32) | 1.41 (1.06, 1.86) |
| 20–25°C | 0.99 (0.94, 1.04) | 0.99 (0.92, 1.06) | 1.10 (0.95, 1.28) | 1.42 (1.09, 1.85) |
| $T_{min}$ & $T_{max}$ >JJA 99th percentile (ref: No) | 1.15 (1.03, 1.29) | 1.15 (0.99, 1.34) | 1.26 (0.89, 1.78) | 1.21 (0.59, 2.47) |

Abbreviations: $AT_{max}$, daily maximum apparent temperature; $T_{min}$ & $T_{max}$, daily minimum and maximum dry-bulb temperatures.

were the focus of all subsequent models. Controlling for season and secular trends, high temperatures the day prior suggested an 17%–18% increase in the risk of spontaneous preterm birth depending on the definition of heat (HR 1.17 (95% CI 1.04, 1.32) for $AT_{max}$ ≥40°C vs. <20°C and HR 1.18 (95% CI 1.06, 1.31) for $T_{max}$ and $T_{min}$ >JJA 99th percentile). Controlling for individual risk factors reduced this to an increase of 15% (HR 1.15 (95% CI 1.01, 1.30) for $AT_{max}$ ≥40°C vs. <20°C and 1.15 (95% CI 1.03, 1.29) for $T_{max}$ and $T_{min}$ >JJA 99th percentile) (Figure 2 and Table S4). The E-value for the association between spontaneous preterm birth and $AT_{max}$ ≥40°C (Model 1 in Table S4) was 1.57, and for the lower CI, it was 1.11. The PAF ranged from 0.024 to 0.027, depending on the racial/ethnic group and definition of heat, suggesting roughly 2.5% or 524 preterm births overall would have been avoided had ambient temperatures not exceeded 40°C (253 Latinx, 97 White, 143 Black, 27 Asian and 4 mixed/other/unknown) based on the alternative (binary) specification of $AT_{max}$ (Table S5).

Censoring births at 28, 32 or 36 weeks resulted in stronger effect estimates of one-day lagged $AT_{max}$ ≥40°C and also suggested higher spontaneous preterm birth risk at ATs between 30 and 40°C (Table 2). For spontaneous preterm birth prior to 28 weeks, the E-values were 5.75 and 2.13 for the HR and lower 95% CI (Table 2).

Although associations with heat were stronger among Black people (HR 1.27 (95% CI 1.01, 1.60) for $AT_{max}$ ≥40°C vs. <20°C and 1.35 (95% CI 1.09, 1.67) for $T_{max}$ and $T_{min}$ >JJA 99th percentile), our analysis did not find statistically significant evidence of effect modification by race/ethnicity (Table 3 and Tables S6–11). We found a positive additive interaction between $AT_{max}$ ≥40°C and residence in the most disadvantaged quintile of ICE. Results using the alternate measure of extreme heat ($T_{max}$ and $T_{min}$ >JJA 99th percentile) were similarly positive for the second most disadvantaged quintile of ICE and also suggested a negative interaction with heat-trapping land cover characteristics on both the multiplicative and additive scales (Table 3 and Tables S6–11).

The effect estimate for the association between $AT_{max}$ ≥40°C and spontaneous preterm birth changed by less than 1%

**TABLE 3** Interaction between extreme heat, race/ethnicity, neighbourhood landcover and ICE

| | Multiplicative (ß) | Additive (RERI) | Effect of heat (HR) |
|---|---|---|---|
| **$AT_{max}$ ≥40°C (ref: <20°C)** | Estimate (95% CI) | Estimate (95% CI) | Estimate (95% CI[b]) |
| Hispanic/Latinx | 0.00 (−0.33, 0.32) | 0.00 (−0.36, 0.37) | 1.11 (0.92, 1.32) |
| White | 0.00 (Reference) | 0.00 (Reference) | 1.11 (0.84, 1.47) |
| Black | 0.13 (−0.22, 0.49) | 0.30 (−0.23, 0.82) | 1.27 (1.01, 1.60) |
| Asian/Pacific Islander | −0.03 (−0.60, 0.54) | −0.02 (−0.69, 0.66) | 1.08 (0.66, 1.79) |
| All others/unknown | 0.40 (−0.70, 1.50) | 0.56 (−1.18, 2.31) | 1.67 (0.57, 4.81) |
| High heat-trapping landcover | −0.06 (−0.45, 0.34) | −0.07 (−0.48, 0.34) | 1.10 (0.75, 1.60) |
| Low heat-trapping landcover | 0.00 (Reference) | 0.00 (Reference) | 1.16 (1.01, 1.33) |
| ICE quintile 1 (most disadvantaged) | 0.37 (−0.05, 0.79) | 0.43 (0.00, 0.85) | 1.28 (1.04, 1.56) |
| ICE quintile 2 | 0.39 (−0.06, 0.83) | 0.44 (−0.02, 0.90) | 1.30 (1.02, 1.66) |
| ICE quintile 3 | 0.18 (−0.31, 0.67) | 0.18 (−0.32, 0.68) | 1.06 (0.76, 1.46) |
| ICE quintile 4 | 0.09 (−0.40, 0.58) | 0.08 (−0.38, 0.55) | 0.97 (0.70, 1.34) |
| ICE quintile 5 (most privileged) | 0.00 (Reference) | 0.00 (Reference) | 0.89 (0.61, 1.28) |
| **$T_{min}$ & $T_{max}$ >JJA 99th percentile (ref: No)** | | | |
| Hispanic/Latinx | 0.06 (−0.26, 0.38) | 0.07 (−0.27, 0.41) | 1.10 (0.94, 1.29) |
| White | 0.00 (Reference) | 0.00 (Reference) | 1.03 (0.78, 1.37) |
| Black | 0.26 (−0.08, 0.61) | 0.47 (−0.03, 0.96) | 1.35 (1.09, 1.67) |
| Asian/Pacific Islander | 0.04 (−0.54, 0.62) | 0.05 (−0.61, 0.71) | 1.08 (0.65, 1.80) |
| All others/unknown | 0.63 (−0.40, 1.67) | 0.82 (−0.94, 2.58) | 1.95 (0.72, 5.27) |
| High heat-trapping landcover | −0.63 (−1.08, −0.17) | −0.55 (−0.87, −0.24) | 0.52 (0.33, 0.81) |
| Low heat-trapping landcover | 0.00 (Reference) | 0.00 (Reference) | 0.97 (0.92, 1.02) |
| ICE quintile 1 (most disadvantaged) | 0.27 (−0.17, 0.71) | 0.28 (−0.13, 0.70) | 1.13 (0.94, 1.35) |
| ICE quintile 2 | 0.46 (0.00, 0.91) | 0.53 (0.07, 1.00) | 1.36 (1.10, 1.68) |
| ICE quintile 3 | 0.25 (−0.24, 0.75) | 0.23 (−0.27, 0.73) | 1.11 (0.83, 1.48) |
| ICE quintile 4 | 0.24 (−0.27, 0.74) | 0.23 (−0.27, 0.73) | 1.09 (0.80, 1.49) |
| ICE quintile 5 (most privileged) | 0.00 (Reference) | 0.00 (Reference) | 0.86 (0.57, 1.29) |

*Note:* Models controlled for secular trend, season and the time-invariant individual-level characteristics described in the text. ß is the coefficient on the relevant interaction term. Positive values for ß and RERI suggest positive interaction on the multiplicative and additive scales, respectively, whereas negative values suggest negative interaction.

Abbreviations: CI, confidence interval; ICE, Index of Concentration at the Extremes; RERI, relative excess risk due to interaction (Rothman 1986 p. 320)[a].

[a] Complete case analysis *N* = 183,414 for race/ethnicity and landcover interaction models. Complete case analysis *N* = 181,809 for ICE interaction models.

[b] Wald confidence limits.

when utilising multiple imputation (HR 1.16 (95% CI 1.03, 1.31)) (Table S12). Utilising PRISM to estimate exposure resulted in attenuated effect estimates and wider CIs, but a similar pattern of greater association between $AT_{max}$ ≥40°C and spontaneous preterm birth at earlier gestational ages (HR 1.11 (95% CI 0.95, 1.30), HR 1.22 (95% CI 0.98, 1.52), HR 2.61 (95% CI 1.65, 4.14) and HR 2.99 (95% CI 0.92, 9.66) in models censored at 37, 36, 32 and 28 weeks, respectively) (Table S13).

## 4 | COMMENT

### 4.1 | Principal findings

We found that maximum apparent temperature ≥40°C was associated with a 15% increase in the risk of spontaneous preterm birth despite the fact that our study population is accustomed to heat. The association was greater between 20 and 36 weeks than it was during the 36th week of pregnancy. While people of colour in our study population were more than twice as likely to live in neighbourhoods with few trees and many heat-trapping surfaces, this appeared to reduce rather than amplify the association between heat and spontaneous preterm birth. Evidence of interaction on the additive scale suggested a greater number of spontaneous preterm births would be prevented if efforts to mitigate heat exposure were focused in neighbourhoods with the greatest concentrations of racialised economic disadvantage.

### 4.2 | Strengths of the study

Our study included a large sample size due to the use of administrative birth records. The survival analysis methods we used provide an advantage over other approaches (e.g. time series) in controlling for confounding due to seasonal variation in the population at risk by comparing people at the same stage of pregnancy regardless of when they conceived. An additional advantage of survival analysis over time series is the ability to control for individual-level risk factors such as education. This is particularly important because seasonal patterns in conception can vary with socioeconomic status.[44]

### 4.3 | Limitations of the data

It is estimated that less than half of conceptions result in live births,[45,46] and one limitation was our lack of information on stillbirths or miscarriages. Several studies suggest that higher ambient temperature during late pregnancy increases the risk of stillbirth.[47–49] Another study found cold temperatures lead to a change in the sex ratio of live births, suggesting differential miscarriage of male foetuses.[50] If extreme heat similarly caused miscarriages, we may have underestimated of the true association between heat and spontaneous preterm birth. Restricting our analysis to live births may have introduced selection bias due to differential foetal loss among those with underlying susceptibility. Although we could not address this issue directly in our analysis, a recent simulation study suggests that live birth bias can lead to an underestimation of the effect of hazardous environmental exposures on pregnancy, particularly for socially disadvantaged populations that are disproportionately exposed.[51]

We included more geographically resolved observations of temperature than most previous studies. However, we could not account for housing characteristics, physical activity levels, air conditioning use and other factors which may have led to non-differential exposure misclassification and larger CIs around our effect estimates. Because we relied on information about induced labour to define our outcome of spontaneous preterm births, we may have included some medically indicated preterm deliveries (e.g. by scheduled caesarean section). We also did not have information on the time of onset of labour, which may have preceded the lag1 and lag2 day temperatures we considered for individuals that experienced long labours.

Our effect estimates may be biased due to unmeasured confounding by factors such as occupation for which we had no information. Personal exposure to ambient heat varies by the ability to control one's work environment, and occupation as a dimension of socioeconomic status may also be associated with preterm birth (although we control for other variables related to socioeconomic status such as education and insurance). With an observed HR of 1.15, the E-value suggests that an unmeasured confounder would need to be associated with both heat and preterm birth by a hazard ratio of 1.57 or greater, above and beyond the measured confounders, to fully explain away the association we observed. An unmeasured confounder would need to be associated with both heat and preterm birth by a hazard ratio of at least 1.11 to move the CI to include the null. It is less likely that an unmeasured confounder could completely explain the observed association between heat and extreme preterm birth prior to 28 weeks, with respective E-values of 5.75 for the HR and 2.13 for the CI.

### 4.4 | Interpretation

Our findings are consistent with other studies from Brisbane, California, Flanders, Guangzhou, Minnesota, Rome and Southern Israel showing an association between heat and preterm birth.[18,28,52–56] These results suggest preterm birth rates will rise with the increased frequency and severity of heatwaves due to climate change. Projections indicate that under a high greenhouse gas emissions scenario, the number of days exceeding 100°F (37.8°C) in our study region will more than double by mid-century (2041–2070).[57] Public health warnings during heatwaves should include pregnant people, especially given our finding of stronger associations earlier in gestation when the consequences of preterm birth are more severe.

## 5 | CONCLUSIONS

High apparent temperatures were associated with increased risk of spontaneous preterm birth in a highly acclimatised population, particularly in neighbourhoods of racialised economic disadvantage, suggesting climate change will increase social inequities in preterm birth rates.

### ACKNOWLEDGEMENTS

This work was supported by the U.S. Environmental Protection Agency (#FP-91744701), the Robert & Patricia Switzer Foundation, the Energy & Resources Group at the University of California, Berkeley and the Alex Farrell Memorial Graduate Fellowship. The U.S. EPA has not formally reviewed this publication, and the views expressed in it are solely those of the authors. The source of data was 2007-2011 birth records provided by the Texas Department of State Health Services, Center for Health Statistics. All interpretations

drawn from these data are those of the authors and not the Texas Department of State Health Services.

## AUTHOR CONTRIBUTION

Lara Cushing (conceptualization, data curation, formal analysis, funding acquisition, methodology, writing - original draft); Rachel Morello-Frosch (funding aquisition, methodology, writing - review & editing); Alan Hubbard (methodology, writing - review & editing)

## DATA AVAILABILITY STATEMENT

The data for this study were obtained from the Texas Department of State Health Services and are not publicly available due to privacy concerns.

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## REFERENCES

1. Blencowe H, Cousens S, Oestergaard MZ, et al. National, regional, and worldwide estimates of preterm birth rates in the year 2010 with time trends since 1990 for selected countries: a systematic analysis and implications. *The Lancet*. 2012;379:2162-2172.
2. Bhutta AT, Cleves MA, Casey PH, Cradock MM, Anand KJS. Cognitive and behavioral outcomes of school-aged children who were born preterm: a meta-analysis. *JAMA*. 2002;288:728-737.
3. Nepomnyaschy L, Reichman NE. Low birthweight and asthma among young urban children. *Am J Public Health*. 2006;96:1604-1610.
4. Doyle LW, Anderson PJ. Adult outcome of extremely preterm infants. *Pediatrics*. 2010;126:342-351.
5. Kuehn L, McCormick S. Heat exposure and maternal health in the face of climate change. *Int J Environ Res Public Health*. 2017;14(8):853.
6. Bekkar B, Pacheco S, Basu R, DeNicola N. Association of air pollution and heat exposure with preterm birth, low birth weight, and stillbirth in the US: a systematic review. *JAMA Netw Open*. 2020;3:e208243.
7. Giorgis-Allemand L, Pedersen M, Bernard C, et al. the influence of meteorological factors and atmospheric pollutants on the risk of preterm birth. *Am J Epidemiol*. 2017;185:247-258.
8. Lee SJ, Hajat S, Steer PJ, Filippi V. A time-series analysis of any short-term effects of meteorological and air pollution factors on preterm births in London, UK. *Environ Res*. 2008;106:185-194.
9. Porter KR, Thomas SD, Whitman S. The relation of gestation length to short-term heat stress. *Am J Public Health*. 1999;89:1090-1092.
10. Wolf J, Armstrong B. The association of season and temperature with adverse pregnancy outcome in two German States, a time-series analysis. *PLoS One*. 2012;7:e40228.
11. Liang Z, Lin Y, Ma Y, et al. The association between ambient temperature and preterm birth in Shenzhen, China: a distributed lag non-linear time series analysis. *Environ Health*. 2016;15:84.
12. Perkins SE, Alexander LV, Nairn JR. Increasing frequency, intensity and duration of observed global heatwaves and warm spells. *Geophys Res Lett*. 2012;39:L20714.
13. Dreiling CE, Carman FS III, Brown DE. Maternal endocrine and fetal metabolic responses to heat stress. *J Dairy Sci*. 1991;74:312-327.
14. Vähä-Eskeli K, Erkkola R. The effect of short-term heat stress on uterine contractility, fetal heart rate and fetal movements at late pregnancy. *Eur J Obstet Gynecol Reprod Biol*. 1991;38:9-14.
15. Lof M, Olausson H, Bostrom K, Janerot-Sjöberg B, Sohlstrom A, Forsum E. Changes in basal metabolic rate during pregnancy in relation to changes in body weight and composition, cardiac output, insulin-like growth factor I, and thyroid hormones and in relation to fetal growth. *Am J Clin Nutr*. 2005;81:678-685.
16. Speakman JR. Obesity and thermoregulation. *Handb Clin Neurol*. 2018;156:431-443.
17. Martin J. Births: final data for 2018. *Natl Vital Stat Rep*. 2019;68:1-46.
18. Basu R, Malig B, Ostro B. High ambient temperature and the risk of preterm delivery. *Am J Epidemiol*. 2010;172:1108-1117.
19. Smith ML, Hardeman RR. Association of summer heat waves and the probability of preterm birth in minnesota: an exploration of the intersection of race and education. *Int J Environ Res Public Health*. 2020;17:6391.
20. Basu R, Hong C, Li DK, Avalos LA. The impact of maternal factors on the association between temperature and preterm delivery. *Environ Res*. 2017;154:109-114.
21. Williams DR, Mohammed SA. Racism and health I: pathways and scientific evidence. *Am Behav Sci*. 2013;57(8):1152-1173. 10.1177/0002764213487340
22. Gronlund CJ. Racial and socioeconomic disparities in heat-related health effects and their mechanisms: a review. *Curr Epidemiol Rep*. 2014;1:165-173.
23. Bailey ZD, Krieger N, Agénor M, Graves J, Linos N, Bassett MT. Structural racism and health inequities in the USA: evidence and interventions. *The Lancet*. 2017;389:1453-1463.
24. Jesdale BM, Morello-Frosch R, Cushing L. The racial/ethnic distribution of heat risk-related land cover in relation to residential segregation. *Environ Health Perspect*. 2013;121:811-817.
25. Nielsen-Gammon JW. The 2011 Texas Drought: a Briefing Packet for the Texas Legislature. 2011. 44 pp. https://senate.texas.gov/cmtes/82/c510/0110BI-JohnNielsen-Gammon.pdf
26. Alexander GR, Himes JH, Kaufman RB, Mor J, Kogan M. A United States national reference for fetal growth. *Obstet Gynecol*. 1996;87:163-168.
27. Strand L, Barnett A, Tong S. Methodological challenges when estimating the effects of season and seasonal exposures on birth outcomes. *BMC Med Res Methodol*. 2011;11:49.
28. Avalos LA, Chen H, Li D-K, Basu R. The impact of high apparent temperature on spontaneous preterm delivery: a case-crossover study. *Environmental Health*. 2017;16:5.
29. Ha S, Liu D, Zhu Y, et al. Ambient temperature and early delivery of singleton pregnancies. *Environ Health Perspect*. 2017;125:453-459.
30. Yackerson N, Piura B, Sheiner E. The influence of meteorological factors on the emergence of preterm delivery and preterm premature rupture of membrane. *J Perinatol*. 2008;28:707-711.
31. Steadman RG. A universal scale of apparent temperature. *J Climate Appl Meteorol*. 1984;23:1674-1687.
32. Homer C, Dewitz J, Yang L, et al. Completion of the 2011 national land cover database for the conterminous United States-Representing a decade of land cover change information. *Photogramm Eng Remote Sensing*. 2015;81:345-354.
33. Krieger N, Waterman PD, Spasojevic J, Li W, Maduro G, Van Wye G. Public health monitoring of privilege and deprivation with the index of concentration at the extremes. *Am J Public Health*. 2016;106:256-263.
34. Stockwell WR, Kramm G, Scheel H-E, Mohnen VA, Seiler W. Ozone formation, destruction and exposure in Europe and the United States. In Sandermann PDH, Wellburn PDAR, Heath PDRL (Eds.). *Forest Decline and Ozone, Ecological Studies* (pp. 1-38). Springer Berlin Heidelberg.
35. Tai APK, Mickley LJ, Jacob DJ. Correlations between fine particulate matter (PM2.5) and meteorological variables in the United States: Implications for the sensitivity of PM2.5 to climate change. *Atmos Environ*. 2010;44:3976-3984.
36. Reid CE, Snowden JM, Kontgis C, Tager IB. The role of ambient ozone in epidemiologic studies of heat-related mortality. *Environ Health Perspect*. 2012;120(12):1627-1630.

37. Hertz-Picciotto I, Rockhill B. Validity and efficiency of approximation methods for tied survival times in Cox regression. *Biometrics*. 1997;53:1151-1156.
38. Kotelchuck M. An evaluation of the kessner adequacy of prenatal care index and proposed adequacy of prenatal care utilization index. *Am J Public Health*. 1994;84:1414-1420.
39. Li R, Chambless L. Test for additive interaction in proportional hazards models. *Ann Epidemiol*. 2007;17:227-236.
40. Rockhill B, Newman B, Weinberg C. Use and misuse of population attributable fractions. *Am J Public Health*. 1998;88:15-19.
41. VanderWeele TJ, Ding P. Sensitivity analysis in observational research: introducing the E-value. *Ann Intern Med*. 2017;167:268-274.
42. Mathur MB, Ding P, Riddell CA, VanderWeele TJ. Web site and R package for computing E-values. *Epidemiology*. 2018;29:e45-e47.
43. PRISM Climate Group. *AN81d (daily) Dataset*. Oregon State University.
44. Darrow LA, Strickland MJ, Klein M, et al. Seasonality of birth and implications for temporal studies of preterm birth. *Epidemiology*. 2009;20:699-706.
45. Boklage CE. Survival probability of human conceptions from fertilization to term. *International Journal of Fertility*. 1990;35(75):79-80, 81-94.
46. Wilcox AJ, Weinberg CR, O'Connor JF, et al. Incidence of early loss of pregnancy. *N Engl J Med*. 1988;319:189-194.
47. Ha S, Liu D, Zhu Y, et al. Ambient temperature and stillbirth: a multi-center retrospective cohort study. *Environ Health Perspect*. 2017;125:0670111-0670117.
48. Kanner J, Williams AD, Nobles C, et al. Ambient temperature and stillbirth: Risks associated with chronic extreme temperature and acute temperature change. *Environ Res*. 2020;189:109958.
49. Strand LB, Barnett AG, Tong S. Maternal exposure to ambient temperature and the risks of preterm birth and stillbirth in Brisbane, Australia. *Am J Epidemiol*. 2012;175:99-107.
50. Catalano R, Bruckner T, Smith KR. Ambient temperature predicts sex ratios and male longevity. *Proc Natl Acad Sci*. 2008;105:2244-2247.
51. Goin DE, Casey JA, Kioumourtzoglou MA, Cushing LJ, Morello-Frosch R. Environmental hazards, social inequality, and fetal loss: Implications of live-birth bias for estimation of disparities in birth outcomes. *Environmental Epidemiology*. 2021;5:e131.
52. Cox B, Vicedo-Cabrera AM, Gasparrini A, et al. Ambient temperature as a trigger of preterm delivery in a temperate climate. *J Epidemiol Community Health*. 2016;70(12):1191-1199.
53. He JR, Liu Y, Xia XY, et al. Ambient temperature and the risk of preterm birth in Guangzhou, China (2001–2011). *Environ Health Perspect*. 2016;124:1100-1106.
54. Schifano P, Lallo A, Asta F, De Sario M, Davoli M, Michelozzi P. Effect of ambient temperature and air pollutants on the risk of preterm birth, Rome 2001–2010. *Environ Int*. 2013;61:77-87.
55. Spolter F, Kloog I, Dorman M, Novack L, Erez O, Raz R. Prenatal exposure to ambient air temperature and risk of early delivery. *Environ Int*. 2020;142:105824.
56. Wang J, Williams G, Guo Y, Pan X, Tong S. Maternal exposure to heatwave and preterm birth in Brisbane, Australia. *BJOG*. 2013;120:1631-1641.
57. Kunkel K, Stevens L, Stevens S, Sun L, Janssen E, Wuebbles D, et al. *Regional Climate Trends and Scenarios for the U.S. National Climate Assessment: Part 4*. Climate of the U.S. Great Plains. National Oceanic and Atmospheric Administration; 2013:91.

## SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

**How to cite this article:** Cushing L, Morello-Frosch R, Hubbard A. Extreme heat and its association with social disparities in the risk of spontaneous preterm birth. *Paediatr Perinat Epidemiol*. 2022;36:13–22. doi:10.1111/ppe.12834