2022

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Citation

Cil, G. and J. Kim, 2022. "Extreme temperatures during pregnancy and adverse birth outcomes: Evidence from 2009 to 2018 U.S. national birth data." *Health Economics*: 1– 30.

Received: 6 September 2021 | Revised: 24 May 2022 | Accepted: 31 May 2022

DOI: 10.1002/hec.4559

RESEARCH ARTICLE

Health Economics WILEY

Extreme temperatures during pregnancy and adverse birth outcomes: Evidence from 2009 to 2018 U.S. national birth data

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Abstract

We provide the first estimates of the impacts of prenatal exposure to extreme temperatures on infant health at birth using the latest national birth data from 2009 to 2018 from all U.S. states. We consistently find that an additional day with mean temperature greater than 80°F or less than 10°F increases preterm births and low birthweight. Strikingly, the adverse effects are borne disproportionately by Black and Hispanic mothers, suggesting that the projected increase in extreme temperatures may further exacerbate the existing birth health disparities across different race/ethnicity groups. We also contribute by investigating the impact of *deviations* from the normal weather pattern, to identify the extreme weather events after accounting for the adaptation response. We find that prenatal exposure to extreme heat two standard deviations above county's historic average induces preterm births and NICU admissions, particularly for mothers whose pregnancies overlap with summer months. These results are timely and policy relevant, considering the recent weather trends with rising temperatures and frequent extreme weather events.

KEYWORDS
birth outcomes, extreme temperatures, infant health, national birth data

JEL CLASSIFICATION
I14, Q51, Q54

1 | INTRODUCTION

A growing consensus about climate change contributing to the gradual warming of the Earth (NASA, 2013) has spurred a literature on the impacts of exposure to extreme temperatures on a range of population health and economic outcomes. There is a burgeoning literature documenting that extreme heat exposure during pregnancy has adverse consequences on birth outcomes, such as preterm birth, stillbirths, and low birthweight, using data from several countries outside of United States (Asamoah et al., 2018; Chen et al., 2020; Chersich et al., 2020; Hajdu & Hajdu, 2021; Li et al., 2018; Martens et al., 2019; Molina & Saldarriaga, 2017; Son et al., 2019). In the United States, only two studies in the economics literature investigated the impacts of in-utero exposure to extreme temperatures on maternal and infant health using national birth data: Deschenes et al. (2009) document that increased number of days exceeding 85°F (29.4°C)[1] during pregnancy reduces birthweight, using the U.S. national birth data from 1972 to 1988.[2] Cil and Cameron (2017) update the findings by using the same data set from 1989 to 2008 and further explore the effects of heat waves during gestation on less common metrics such as abnormal conditions of the newborn (fetal distress, usage of ventilator after birth, and meconium aspiration) and adverse health conditions of the mother (gestational hypertension, eclampsia, and uterine bleeding). To our knowledge, there has been no attempt to update the findings using the U.S. national birth data from the latest decade starting 2009.

Preterm birth and low birthweight impose an immense burden with both short-term and long-term costs to the society. A higher rate of mortality and morbidity arises from babies born preterm or with low birthweight, resulting in substantial costs to the health sector following the infant's initial discharge from hospital (Petrou et al., 2001). There is a wealth of evidence on the lasting effects of early life circumstances indicating that adverse birth outcomes are highly associated with lower levels of education, income, or depression during adulthood (Barker, 1990; Almond & Currie, 2011a,2011b; Almond et al., 2018). In this regard, examining the effects of prenatal exposure to extreme temperatures on infant health is crucial given its substantial costs to one's life and to the society.

As the extreme temperature events become more prevalent worldwide, the U.S. provides a unique opportunity for researchers to examine the health impacts of exposure to extreme heat for several reasons. First, the U.S. spans across a large area covering several distinct temperature regions, which enables researchers to use the substantial variation in temperature exposure based on location while taking advantage of health outcomes data collected in a consistent manner across regions and over time. Secondly, the U.S. has a diverse population with widely documented racial/ethnic disparities in infant health outcomes, facilitating and motivating further investigations into how climate change can exacerbate the racial/ethnic gap in infant health as ambient temperatures are projected to rise in the coming decades. Lastly, the U.S. is one of the most climate-adapted countries in the world with high rates of air-conditioning adoption. Hence, it is informative to explore how the effects of extreme heat on infant health have evolved over time, after taking this recent adaptative techniques into account.

The goal of this study is to expand the previous studies and further the understanding of the effects of prenatal exposure to extreme temperatures on birth outcomes, such as preterm birth, low birthweight, and Neonatal Intensive Care Unit (NICU) admissions, using the *latest* weather data from 2009 to 2018 matched with the universe of birth records in the U.S. Our paper builds on the existing literature in three ways. Foremost, we deliver the first estimates of the impacts of prenatal temperature exposure on infant health with the latest U.S. national birth data from 2009 to 2018. The results are particularly timely and policy relevant, in the light of the recent weather trends with a rising ambient temperature and more frequent extreme weather events. Specifically, a recent climate report (Climate Central, 2021) documents that nine of the warmest years globally have all occurred since 2009, with the exception of 2005. The National Oceanic and Atmospheric Administration (NOAA) indicates each year in the current decade (2019–2028) to be ranked among the top 10 warmest years globally, given historical observations and persistent long-term climate change trends. Therefore, it is critical to continue examining the impact of prenatal exposure to extreme temperatures on birth outcomes, accounting for the latest weather trend and adaptation to the rising temperatures.

Second, our usage of *relative* temperature measures in addition to conventional absolute measures in Fahrenheit (Hsiang, 2016) sheds light on an alternative way to identify the *extreme* temperatures. For example, the same 80°F (26.7°C) day in March could lead to substantially different behavioral responses for a mother in Florida versus a mother in Michigan. Accordingly, we model temperature exposure in terms of deviations from each county's historical monthly mean, and define extreme heat if temperature is two standard deviations (SD) *above* the mean and extreme cold if temperature is 2SD *below* the mean. The same method was first used in a recent paper, Kim et al. (2021). However, we move beyond what was used in Kim et al. (2021) and also add a new relative temperature measure, using the *average over the year* instead of monthly mean, and create "hot-cutoffs" and "cold-cutoffs" for every county and year. Our usage of relative temperature measures account for the substantial variation in average temperatures across geographic regions that could generate heterogeneity in adaptation responses (Barreca et al., 2015, 2016; Carleton et al., 2018; Deschenes & Greenstone, 2011; Graff Zivin & Neidell, 2014; Kim et al., 2021) and underscore the importance of interpreting the estimates according to appropriate measures and corresponding contexts.

Lastly, we explore the heterogeneous effects of exposure to extreme temperatures across different racial/ethnic groups to provide important insights into the potential determinants of birth health disparities, which have been rising in recent years in the U.S. (Kassebaum et al., 2016).[3] We find that adverse birth outcomes are more sizable for Black and Hispanic infants, and this emphasizes the differences in exposure to extreme heat along racial/ethnic and socioeconomic lines due to both the differences in residence locations and differential adoption of defensive investments by race/ethnicity such as air conditioning or heating technologies (Gronlund, 2014; Hoffman et al., 2020; O'Neill et al., 2005). Our results offer the latest evidence of a potential contributing factor to racial/ethnic disparities in birth outcomes, suggesting that climate change may exacerbate the already large racial/ethnic gap in infant health.

To identify a plausibly causal relationship between temperature and birth outcomes, we follow the literature (e.g., Isen et al., 2017; Kim et al., 2021) and leverage arguably random variation in extreme temperature exposure over time within narrowly defined geographic, temporal and demographic cells. Specifically, our models control for mother's demographic characteristics as well as mother's county-birth month fixed effects and mother's state-birth year fixed effects. This specification allows us to flexibly account for region-specific seasonality of birth outcomes and unobserved spatial and timewise heterogeneity in temperatures and birth outcomes, as well as socio-demographic characteristics of mothers.

Our results point to small but statistically significant impacts of exposure to extreme heat during pregnancy on infant health. We find that an additional day during pregnancy with an average daily temperature between 80 and 90°F (26.67–32.2°C) leads to an additional 0.026 infant with low birthweight per 1000 births, corresponding to an effect size of 0.1%. An additional hot day with a mean over 90°F (32.2°C) increases extremely preterm births by 0.014 in 1000 births with an effect size of 0.24% of the mean and also increases NICU admissions by 0.153 per 1000 births, with an effect size of 0.2%. We document that the changes in preterm birth and low birthweight outcomes associated with extreme temperatures are driven by the adverse impact on non-Hispanic Black and Hispanic births, while increases in NICU admissions are observed among non-Hispanic White and Hispanic births. Our estimates stay robust when we include placebo temperature exposures or when air quality index (AQI) is additionally controlled for. We also show that there are no systematic correlations between our measure of prenatal temperature exposure and mother's demographic characteristics, including race, education, and marital status.

We believe that our work contributes to the existing literature on the adverse impacts of extreme temperatures on infant health by confirming the existing findings in the literature with more up-to-date data from the U.S. and robust approaches to the analyses, and by documenting the disproportionate impact on racial and ethnic minorities.

2 | BIOLOGICAL MECHANISMS BETWEEN TEMPERATURE AND HEALTH

A growing medical literature suggests that exposure to extreme temperature can be particularly risky for pregnant women and the fetus. When body temperature increases (or decreases), blood flow shifts from the vital organs to underneath the skin's surface to facilitate cooling (or heating) (Astrand et al., 2003). When too much blood is diverted, the body's capacity to regulate its temperature may be hindered, which particularly puts increased stress on pregnant women who are not able to regulate temperature as efficiently as they were during pre-pregnancy period, due to the physiologic changes during gestation (Dadvand et al., 2011; Schifano et al., 2016; Auger et al., 2017; Ha et al., 2017a, b).

While there is limited evidence of the effects of cold temperatures and birth defects (Zutphen et al., 2013), a robust medical literature points to the biological mechanisms through which extreme heat could be damaging to pregnant women. Specifically, heat exposure can alter placental blood flow patterns, which can reduce the integrity of the placenta and increase the chance of abruption (He et al., 2018). Heat could also raise the likelihood of other serious pregnancy complications, including hypertension, preeclampsia, and prolonged premature rupture of membranes (Beltran et al., 2014; Yackerson et al., 2007). In addition, elevated temperature can increase the fetal heart rate and lead to uterine contractions (Vaha-Eskeli & Erkkola, 1991). In turn, embryos and fetuses are adversely affected by elevated maternal temperatures due to their developing central nervous systems (Edwards et al., 2003). All of these issues can translate into women suffering from pregnancy complications, and newborns experiencing adverse outcomes at birth.

In sum, there are clear biological reasons to support the idea that exposure to extreme temperatures during pregnancy could be damaging for both mothers and fetuses. The goal of this paper is to use the latest national U.S. birth data with a rigorous research design to quantify these impacts, thereby shedding light on the effects of prenatal exposure to extreme temperature as well as the environmental determinants of health at birth.

3 | DATA

3.1 | National Vital Statistics Birth Data

We use data on all singleton births that have occurred in the period 2009–2018 in the contiguous U.S. from the restricted-use version of the National Vital Statistics System Natality Detail Files (NCHS, 2019). These data are based on the birth certificates, and include information on each newborn, such as month and year of birth, sex, birthweight, and gestational age. The data also contain information on the mother, including age, race/ethnicity, marital status, education, and county of residence. We include all births with complete information on at least one of the health outcomes we study, the county of residence and all other socio-demographic information for the mother.

We focus on the birthweight- and gestational age-related outcomes that are often considered as the standard measures of health at birth, as well as neonatal intensive care unit (NICU) admissions and any assisted ventilation immediately after birth, and whether mother was diagnosed with gestational hypertension during pregnancy. The birthweight- and gestational age-related outcomes include dichotomous variables indicating (1) preterm birth (gestational age less than 37 weeks), (2) very preterm birth (gestational age less than 32 weeks), (3) extremely preterm birth (gestational age less than 28 weeks), (4) low birthweight (birthweight less than 2500 g), (5) very low birthweight (birthweight less than 1500 g), and (6) preterm AND low birthweight.[4] The cutoffs for preterm birth and low birthweight are as defined in the 10th Revision of the International Classification of Disease, ICD-10 (low birthweight disease code: P07.1, prematurity disease code: P07.3). Very low birthweight and very preterm cutoffs, on the other hand, are based on the definitions used in National Vital Statistics Reports by the Centers for Disease Control and Prevention (e.g., Hamilton et al., 2015), and extremely preterm definition is the one used by American College of Obstetricians and Gynecologists (ACOG, 2019) and in the World Health Organization reports (e.g., WHO, 2018).

3.2 | GHCND weather data

To measure temperature exposure during pregnancy, we use detailed weather data constructed from the GHCN daily (GHCND), maintained by the National Oceanic and Atmospheric Administration (NOAA). We obtain information on average, maximum, and minimum daily ground temperature and precipitation levels for every county[5] and every month during the years 2009–2018.[6] We merge the GHCND weather data with the National Vital Statistics data using the mother's county of residence reported at the time of childbirth as well as the month and year of delivery. We assign prenatal temperature exposure assuming a 40-week gestational age for all observations,[7] counting nine months backward from birth month. This will likely introduce measurement errors– for example, for mothers who give birth a few weeks earlier than due date, the temperature exposure that we assign during the first few weeks of pregnancy would be irrelevant.[8] However, we argue that the benefit of using 40-week gestational age for everybody outweighs the costs associated with measurement errors for some observations. We also try using 36-week gestational age for everybody counting eight months backward from birth month to exclude the 4-week period around the time of conception to address concerns about selection into fertility (Barreca et al., 2018) as a robustness check. Our final sample includes 34.7 million births.

We measure prenatal temperature exposures in two ways. First, we follow the conventional approach in the existing literature by using 10 temperature (Fahrenheit) bins (<10, 10–20, 20–30, …, 80–90, >90°F) and counting the number of days in each bin where daily average temperature falls during pregnancy.[9] Second, we normalize daily temperature relative to the historical average for each county-month combination (Beatty et al., 2014; Kim et al., 2021). In other words, for every county, we first construct a z-score for each day by calculating the difference between average daily temperature and the county's average temperature for that calendar month based on data from all years from 2007 to 2018, and dividing by the standard deviation. We then calculate the number of days in each county-month that fall in the following seven standard deviation (SD) temperature bins: <-3SD, -3SD to -2SD, -2SD to -1SD, -1SD to 1SD, 1SD to 2SD, 2SD to 3SD, >3SD. This method allows us to identify the extreme *deviations* from typical weather in a given month and county, while accounting for adaptation to long-term weather trends. An extreme weather event that falls outside the realm of normal patterns may be particularly damaging to health outcomes. We are interested in days with average temperature at least two SDs above or below the county's overall monthly mean to quantify the impact of extreme heat or extreme cold.

3.3 | Distribution of temperature exposure

Figure 1 shows the number of days in each state and year with at least one county in the state experiencing average temperatures above 80°F. This figure illustrates that there is a substantial geographic variation in exposure to extreme temperatures with number of such days varying between zero and 216 in the U.S. While some states consistently have a large number of extremely hot days (e.g., Texas, Florida, Arizona, etc.) and some consistently have only few (e.g., New England sub-region), several states have considerable variation in number of days with extremely hot temperatures over the years.

Figure 2 and Table 1 show the distribution of average number of days during the typical pregnancy falling into each of the absolute and relative temperature bins. On average, pregnant women in our sample spent 31 days with mean temperature 80–90°F and about 2 days with mean temperature above 90°F during pregnancy. Using relative temperatures, on average, pregnant women in our sample had 5 days with two to three SD deviations above the county-monthly mean temperature and 0.2 of days with above-3-SD temperatures during pregnancy.

It is noteworthy to compare the extreme temperature exposure we observe in our data with that from Deschenes et al. (2009). They show, using the U.S. weather data between 1972 and 1988, that women experience on average 3.8 days with mean temperature greater than 85°F over the course of typical pregnancy. The number of days during pregnancy with mean temperature over 85°F in our data is 10.3 days (not shown in Table 1), which is 2.7 times higher than the average number of days approximately 30 years ago, which confirms the recent weather trends with a rising ambient temperature.

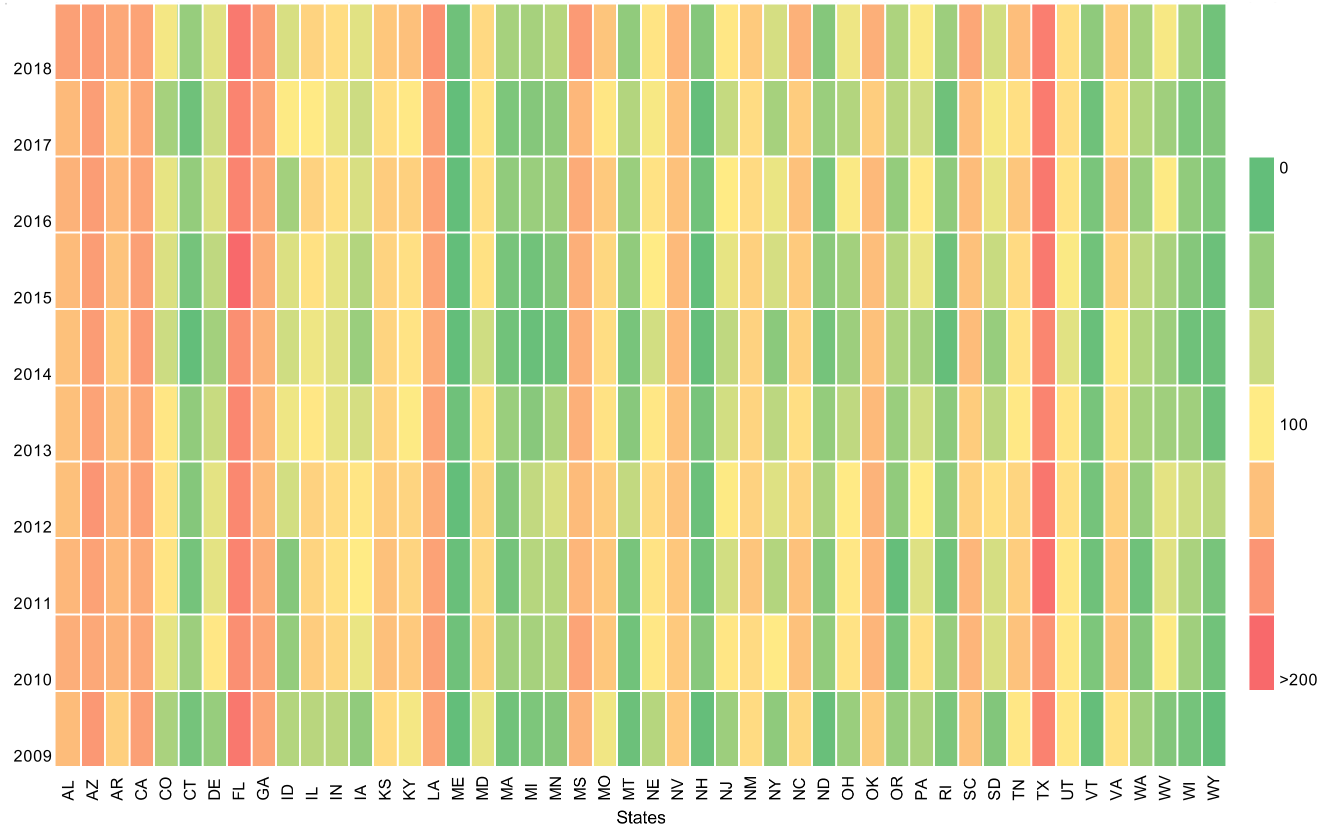

FIGURE 1 Distribution of Hot Days above 80°F Across States and Years. Each bar shows the number of days in a given state and year with at least one county in the state experiencing daily average temperature above 80°F. *Sources*: GHCN daily (GHCND) weather data 2009–2018.

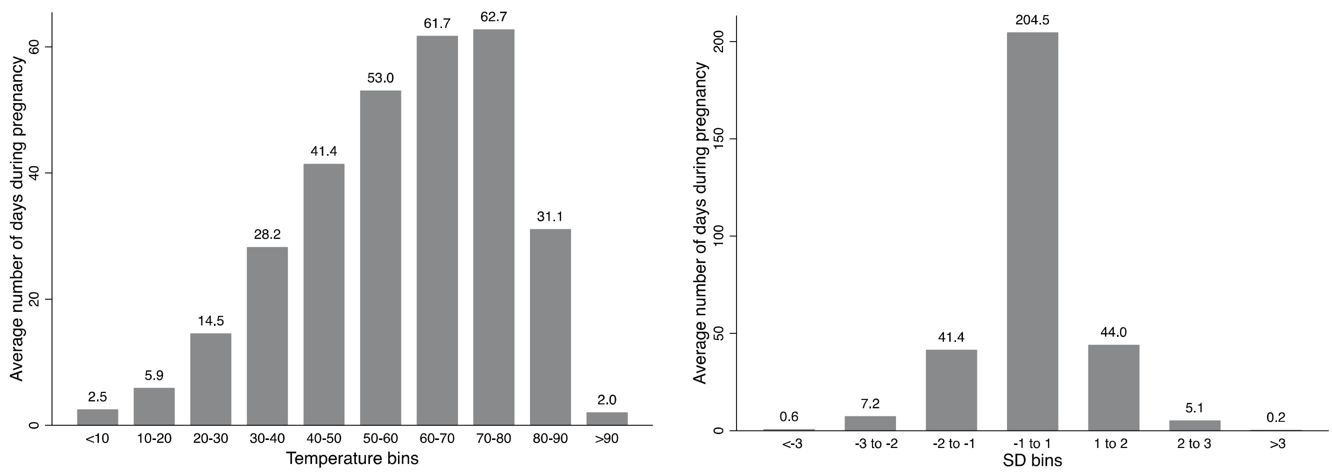

FIGURE 2 Distribution of Daily Average Temperature during Pregnancy. Each bar shows the average number of days during pregnancy with mean temperature in the corresponding temperature range defined in absolute temperature bins measured in Fahrenheit (left), and in relative temperature bins measured in terms of deviation from the county-month historic mean temperature (right). *Sources*: GHCN daily (GHCND) weather data merged with U.S. National Vital Statistics Birth Data 2009–2018.

Exposure to high temperatures varies widely by birth month (Appendix Table 1). On average, pregnancies that have greater overlap with summer months (i.e., births occurring July through December, noted as "High exposure" group) had 34.2 days during pregnancy with mean temperature 80–90°F and 2.23 days with mean temperature above 90°F. On the other hand, pregnancies that have less overlap with summer months (i.e., births occurring January through June, noted as "Low exposure" group) have 27.8 days with mean temperature 80 to 90°F and 1.74 days with mean temperature above 90°F.[10] Furthermore, Table A1 provides suggestive evidence that exposure to extreme temperatures during pregnancy may not be equal across

TABLE 1 Summary statistics

Panel A. Exposure to temperature	
Average number of days during pregnancy with mean temperature	
Relative	
>3SDs below mean	0.594
2–3 SDs below mean	7.229
2–3 SDs above mean	5.094
>3SDs above mean	0.194
Absolute	
<10F degrees	2.474
10–20F degrees	5.872
80–90F degrees	31.065
>90F degrees	1.992
Panel B. Birth outcomes (per 1000 births)	
Preterm birth (<37 weeks of gestation)	98.706
Very preterm birth (<32 weeks of gestation)	15.346
Extremely preterm birth (<28 weeks of gestation)	5.76
Low birthweight (<2500 g)	63.337
Very low birthweight (<1500 g)	10.799
Preterm and low birthweight	38.911
NICU Admission	74.175
Assisted ventilation immediately after birth	34.75
Gestational hypertension	50.35
Panel C. Maternal characteristics (%)	
Race/Ethnicity	
Non-hispanic white	56.018
Non-hispanic black	16.358
Hispanic	18.349
Other	9.275
Age	
<18	2.052
18–22	17.315
23–28	32.363
29–34	32.627
≥35	15.643
Education	
Less than high school	15.727
High school	25.048
Some college	28.346
College or more	30.878
Marital Status	
Married	59.579
N	366,265

Notes: For panels B and C, we use the data collapsed at the race×birth-county×birth-year-month level. Cell size weights are used.

Sources: GHCND weather data merged with U.S. National Vital Statistics Birth Data 2009–2018.

different race/ethnicity groups. The data shows that Hispanic mothers disproportionately experienced more days with temperature above 80°F as well as with above-3SD-heat.

In addition to the exposure to extreme temperatures during pregnancy, Table 1 Panel B and C presents summary statistics of our main birth outcomes as well as mother's demographic characteristics. Out of 1000 births, approximately 99 were preterm, 15 were very preterm, and 6 were extremely preterm in the analysis period of 2009–2018. About 63 out of 1000 newborns had low birthweight and 11 had very low birthweight, while 74 out of 1000 were admitted to NICU immediately after birth.

4 | EMPIRICAL STRATEGY

4.1 | Econometric approach

The key goal of this study is to identify the causal effects of prenatal exposures to extreme temperatures on infant's birth outcomes. However, variations in temperature exposure during pregnancy among mothers is far from random and thus suffer from omitted variable bias. There could be selection into geographic regions based on personal preferences, income level, school district, or the cost of living. Furthermore, Buckles and Hungerman (2013) document that there exists substantially different socioeconomic characteristics based on the month of birth, because summer months differentially affect fertility patterns across socioeconomic groups, which suggests possible selection into conception. Accordingly, without taking these factors into account, simple comparisons across mothers residing in different counties who give births in different months would lead to biased estimates.

To address this challenge, we follow the prior studies and make use of temperature variation within narrowly defined geographic, temporal and demographic cells (Kim et al., 2021). We aggregate individual-level data at race-birth county-birth year and birth month level defined by possible combinations of mother's race group (non-Hispanic White, non-Hispanic Black, Hispanic, and other non-White non-Hispanic race), mother's county of residence, and year and month of birth. We only include cells with at least 10 births. This allows us to identify the effects of the temperature variation among mothers who are placed in the same cell. Furthermore, given the size of the data set of all national births from 2009 to 2018, using the collapsed data lessens the computational burden, while producing the similar estimates from the individual-level data when using the correct cell-size weight.

The total number of observations in our study is 366,265 county-year-month-race group cells each with at least 10 births, which come from 32,271,928 singleton births over the period of 2009–2018 with complete information on at least one outcome and mother's socio-demographic characteristics.[11]

We estimate the changes in birth outcomes associated with exposure to extreme temperatures using the following equation:

$$Y_{rcym} = \sum_{j=1}^{10\,or\,7} \beta_j \text{Temp}_{cym}^{j} + f(\text{Precipitation})_{cym} \cdot \gamma + X_{rcym}{}'\delta + \alpha_{sy} + \alpha_{rcm} + \epsilon_{rcym} \tag{1}$$

Y_{rcym} denotes an outcome variable indicating the rate per 1000 infants born in county c, in year y month m in race group r. The variable $Temp_{\mathrm{cym}}^{j}$ denotes the number of days falling into temperature bin j, where j ranges from 1 to 10 for absolute Fahrenheit temperature bins and 1–7 for relative SD temperature bins. As a reference group, we omit the −1 SD to 1 SD bin for the relative temperature analysis and 60 to 70°F bin for absolute temperature analysis, such that β_j , our coefficients of interest, represent the estimated impact of an additional day of exposure to temperatures in temperature bin j relative to a day in the reference temperature bin. We also control for rainfall flexibly by including indicators for the upper and lower terciles of mean precipitation during pregnancy, $f(\boldsymbol{Precipitation})_{cym}$. X_{rcym} is a vector of covariates including the percentage of mothers in each age group [aged 22–25 (reference category), 26–29, 30–34, and greater than 35], education level [less than high school education (reference category), only high school education, and college education or more], and marital status.[12] We include state-by-year fixed effects (α_{sy}) to flexibly account for any year-to-year changes in the outcomes common to all births in a state due to, for instance, changes in state-level policies. Given that we collapse our data into race-birth county-birth year-month cells, it is imperative that we include fixed effects with consideration to heterogeneity at the same level. α_{rcm} denotes race group-by-county-by-birth month fixed effects which account for seasonality of birth outcomes allowing it to be specific to county and race group. We acknowledge that this model may be over-specifying and thus may have some constraints. In the robustness check, we show that our results are robust to the choice of specification by including different combinations of fixed effects. We weight all regressions by cell size and cluster standard errors on the commuting zone level.[13]

One might point to a concern that temperature variation left after including all the fixed effects might be too minimal to identify the effects. Figure 3 presents, however, that there is sufficient variation left in the highest temperature bins, both absolute and relative measures, even after including all the fixed effects in the model.

4.2 | Identifying assumption

The identifying assumption for our estimate to be plausibly causal is that temperature variation within each defined cell should not be correlated with other determinants of birth outcomes, such as mother's demographic characteristics. We address the possibility of potential confounding effects of changes in socioeconomic characteristics of mothers by running a placebo outcome test. We collapse the data to birth county and birth year-month level and run the Equation (1) but replace outcomes with mother's race, marital status, and education level. Table A2 shows that extreme temperature exposures (both extreme hot and cold bins, regardless of using absolute or relative measures) are not systematically associated with any of the mother's demographic characteristics.

We also examine the relationship between extreme heat and the newborn sex ratio at birth, finding no significant reduction in proportion of male newborns associated with extreme temperatures (Results not shown, available upon request.) This suggests that there is no significant effect on miscarriages, as it is widely documented that male fetuses are more vulnerable to side effects of maternal stress in utero (e.g., Catalano et al., 2005; Sanders & Stoecker, 2015).

5 | RESULTS

5.1 | Main results

5.1.1 | Effects of absolute temperatures during pregnancy on birth outcomes

The results of the model with absolute temperature bins are given in Table 2. These results indicate that exposure to average temperatures above 90°F increases the risk of very preterm birth, extremely preterm birth, and NICU admission. Specifically, an additional day during pregnancy with average daily temperature above 90°F leads to an additional 0.013 very preterm birth in 1000 births which corresponds to an effect size of about 0.1% when evaluated at the sample mean. Similarly, an additional day with average daily temperature above 90°F leads to an additional 0.014 extremely preterm birth in 1000 births, or a 0.24%

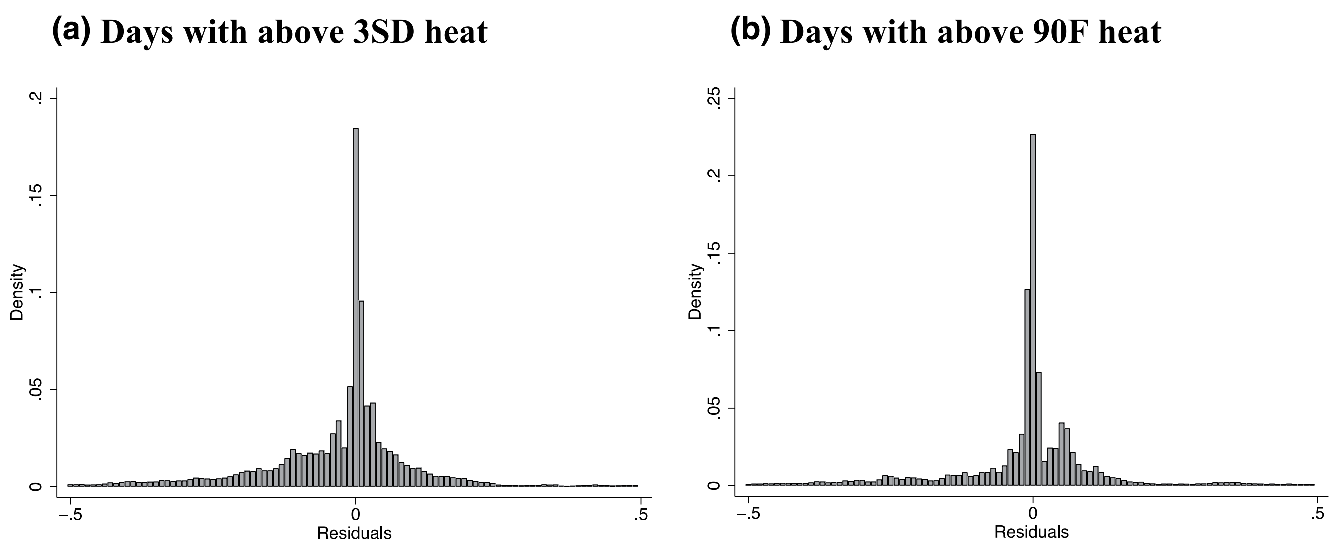

FIGURE 3 Distribution of Residuals in Temperature after Controlling for All Fixed Effects. (a) Days with above 3SD heat and (b) Days with above 90F heat. The residuals are derived from a regression of the number of days in top temperature bins on race-by-birth county-by-birth month fixed effects and birth state-by-birth year fixed effects. *Sources*: GHCN daily (GHCND) weather data merged with U.S. National Vital Statistics Birth Data 2009–2018.

TABLE 2 Effects of absolute temperatures during pregnancy on birth outcomes

	Number of births with adverse outcomes (in 1000 births)					
	Preterm birth	Very preterm birth	Extremely preterm birth	Low birthweight	Very low birthweight	NICU admission
# Days below 10F	0.055	0.028**	0.005	0.017	0.003	0.029
	(0.04)	(0.01)	(0.007)	(0.03)	(0.01)	(0.06)
# Days 10–20F	0.021	−0.008	−0.006	−0.006	−0.008	−0.001
	(0.03)	(0.01)	(0.006)	(0.02)	(0.01)	(0.08)
# Days 20–30F	0.052**	0.000	0.006	0.019	0.006	−0.05
	(0.02)	(0.01)	(0.004)	(0.02)	(0.01)	(0.06)
# Days 30–40F	0.019	−0.007	−0.000	0.012	−0.006	−0.03
	(0.02)	(0.01)	(0.003)	(0.01)	(0.00)	(0.04)
# Days 40–50F	0.025	0.003	0.001	0.020**	−0.002	0.013
	(0.02)	(0.01)	(0.003)	(0.01)	(0.00)	(0.03)
# Days 50–60F	0.016	−0.001	0.003	0.005	0.002	0.008
	(0.01)	(0.00)	(0.002)	(0.01)	(0.00)	(0.04)
# Days 70–80F	0.024**	0.003	0.003*	0.01	0.002	0.013
	(0.01)	(0.00)	(0.002)	(0.01)	(0.00)	(0.02)
# Days 80–90F	0.006	0.006	0.004	0.026***	0.008**	0.042
	(0.02)	(0.01)	(0.003)	(0.01)	(0.00)	(0.05)
# Days above 90F	−0.02	0.013*	0.014***	−0.006	0.007	0.153*
	(0.03)	(0.01)	(0.004)	(0.02)	(0.01)	(0.09)
Observations	366,265	366,265	366,265	366,265	366,265	347,441
R-squared	0.492	0.342	0.278	0.511	0.323	0.287
Adj. R^2	0.413	0.24	0.166	0.435	0.217	0.17
Mean	98.706	15.346	5.760	63.337	10.799	74.175

Notes: Each column reports regression coefficients (β_j) from Equation (1). Temperature bin 60–70F is omitted as a reference group. Robust standard errors, clustered by commuting zone, are in parentheses. We use the data collapsed at the race×birth-county×birth-year-month level. Cell size weights are used.

*$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

Sources: GHCND weather data merged with U.S. National Vital Statistics Birth Data 2009–2018.

of the mean increase in extremely preterm birth. NICU admissions, on the other hand, increase by 0.153 per 1,000, corresponding to an effect size of 0.2%, in relation to an additional day with average daily temperature above 90°F.

Additionally, exposure to temperatures between 80 and 90°F leads to small but statistically significant increases in the risk of low birthweight or very low birthweight. An additional day during pregnancy with an average daily temperature between 80 and 90°F leads to an additional 0.026 births with low birthweight per 1000 births and an additional 0.008 births with very low birthweight per 1000 births, each of which correspond to an effect size of less than 0.1%. We also find that exposure to average temperatures below 10°F increase the likelihood of very preterm birth by about 0.03 in 1000 births, corresponding to effect size of about 0.2%. We do not find any statistically significant increase associated with extreme temperatures in births who are both preterm and low birthweight, births requiring assisted ventilation, and gestational hypertension (See Table A3 Panel A.).

5.1.2 | Effects of relative temperatures during pregnancy on birth outcomes

The results of the model with relative temperature bins, given in Table 3 and Appendix Table 3 Panel B, indicate no statistically discernible impact associated with extreme temperature deviations from the county temperature norm. Exposure to temperatures that are 2-3SD below the mean, on the other hand, is correlated with an increase in the risk of preterm or very preterm birth. Specifically, an additional day with 2-3SD below mean temperatures leads to 0.088 per 1000 increase in preterm births (0.1% of the mean) and 0.021 per 1000 increase in very preterm births (0.13% of the mean). However, caution should be made

TABLE 3 Effects of relative temperatures during pregnancy on birth outcomes

	Number of births with adverse outcomes (in 1000 births)					
	Preterm birth	Very preterm birth	Extremely preterm birth	Low birthweight	Very low birthweight	NICU admission
# Days >3 SD below mean	−0.068	0.01	−0.001	−0.006	−0.004	0.489
	(0.09)	(0.03)	(0.017)	(0.06)	(0.02)	(0.51)
# Days 2-3 SD below mean	0.088*	0.021*	0.006	−0.003	0.004	−0.219
	(0.05)	(0.01)	(0.005)	(0.02)	(0.01)	(0.21)
# Days 1-2 SD below mean	−0.014	−0.007	−0.003	−0.002	−0.005*	0.074**
	(0.02)	(0.00)	(0.002)	(0.01)	(0.00)	(0.03)
# Days 1-2 SD above mean	−0.012	0.003	0.002	0.004	0.002	0.057**
	(0.02)	(0.00)	(0.002)	(0.01)	(0.00)	(0.03)
# Days 2-3 SD above mean	0.061	0.001	−0.002	−0.004	−0.016**	0.143
	(0.04)	(0.01)	(0.005)	(0.02)	(0.01)	(0.10)
# Days >3 SD above mean	0.118	−0.008	−0.012	−0.069	−0.017	0.107
	(0.28)	(0.06)	(0.022)	(0.08)	(0.03)	(0.60)
Observations	366,265	366,265	366,265	366,265	366,265	347,441
R-squared	0.49	0.34	0.278	0.51	0.32	0.29
Adj. R^2	0.413	0.24	0.166	0.435	0.217	0.17
Mean	98.71	15.35	5.760	63.34	10.80	74.18

Notes: Each column reports regression coefficients (β_j) from Equation (1). Temperature bin -1SD to +1SD is omitted as a reference group. Robust standard errors, clustered by commuting zone, are in parentheses. We use the data collapsed at the race×birth-county×birth-year-month level. Cell size weights are used.

*$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

Sources: GHCND weather data merged with U.S. National Vital Statistics Birth Data 2009–2018.

when we interpret the relative temperature measures: below-2SD-cold during summer months implies cooler-than-normal summer, which may not be as harmful as below-2SD-cold during winter months.

Therefore, in Table 4, we split our sample by the extent of exposure to summer months during pregnancy. We find that, for births with greater exposure to summer months during gestation (i.e., High-exposure group), extreme heat leads to increases in preterm births and NICU admission. An additional hot day with temperatures 2-3SD above the mean leads to an additional 0.104 preterm birth per 1000 (0.1% of the mean) and an additional 0.295 NICU admissions in 1000 births (0.4% of the mean). However, the same above-2SD-heat day appears to decrease the probability of low birthweight when the pregnancies had greater exposure to winter months (i.e., Low-exposure group).

Exposure to extreme cold, on the other hand, increases the risk of preterm or very preterm birth across the board. In other words, cooler-than-usual summer days during pregnancy (below-2SD-cold for High-exposure group) is still correlated with a chance of having preterm births, similar to colder-than-usual winter days during pregnancy (below-2SD-cold for Low-exposure group). Specifically, an additional cold day with temperatures 2-3SD below the mean increases the likelihood of preterm birth for both groups by about 0.13% of the mean. Yet, we find no effects of extreme cold on birthweight or NICU admission.

5.1.3 | Effects of absolute temperatures during pregnancy on birth outcomes: By race/ethnicity

We find that the adverse impacts of exposure to extreme temperatures vary by mother's race/ethnicity. Table 5 shows the estimated impacts of additional days of exposure to extreme temperatures below 10°F, between 80 and 90°F, and above 90°F by mother's race/ethnicity when the model given in Equation (1) is estimated separately for mothers in each of the four race/ethnicity groups, non-Hispanic White, non-Hispanic Black, Hispanic and other race/ethnicity. These results indicate non-Hispanic Black and Hispanic births are most vulnerable to exposure to both extremely low and extremely hot temperatures.

More specifically, when evaluated at the sub-group mean, an additional day of exposure to average temperature below 10°F increases the risk of very preterm birth, low birthweight, and very low birthweight only among births to non-Hispanic Black mothers by about 0.5%, 0.2%, and 0.45%, respectively. The NICU admissions, on the other hand, appear to increase only among Hispanics in response to an additional day of exposure to average temperature below 10°F with an effect size of 0.7%.

TABLE 4 Effects of relative temperatures during pregnancy on birth outcomes, by exposure to summer months during pregnancy

	High-exposure group: Number of births with adverse outcomes (in 1000 births)						Low-exposure group: Number of births with adverse outcomes (in 1000 births)					
	Preterm birth	Very preterm birth	Extremely preterm birth	Low birthweight	Very low birthweight	NICU admission	Preterm birth	Very preterm birth	Extremely preterm birth	Low birthweight	Very low birthweight	NICU admission
# Days >3 SD Below mean	0.010	0.077**	−0.014	0.005	0.015	0.435	−0.060	−0.050	−0.000	−0.037	−0.006	0.054
	(0.117)	(0.036)	(0.022)	(0.080)	(0.028)	(0.356)	(0.131)	(0.046)	(0.025)	(0.077)	(0.030)	(0.280)
# Days 2-3 SD Below mean	0.124*	0.006	0.008	−0.024	−0.000	−0.143	0.139**	0.033**	−0.007	0.020	0.005	0.046
	(0.071)	(0.014)	(0.006)	(0.031)	(0.010)	(0.174)	(0.060)	(0.016)	(0.009)	(0.028)	(0.011)	(0.101)
# Days 1-2 SD Below mean	−0.012	−0.005	−0.002	0.009	0.000	0.085**	−0.008	−0.008	−0.002	−0.007	−0.010*	0.074*
	(0.022)	(0.006)	(0.003)	(0.011)	(0.004)	(0.034)	(0.024)	(0.007)	(0.003)	(0.014)	(0.005)	(0.042)
# Days 1-2 SD Above mean	−0.015	−0.000	0.002	0.004	0.001	0.027	−0.001	0.004	−0.000	0.004	0.003	0.092**
	(0.018)	(0.006)	(0.003)	(0.011)	(0.004)	(0.039)	(0.021)	(0.005)	(0.003)	(0.013)	(0.004)	(0.037)
# Days 2-3 SD Above mean	0.104**	−0.009	−0.002	−0.018	−0.016	0.295***	0.040	0.003	−0.004	0.013	−0.023**	0.132
	(0.051)	(0.015)	(0.008)	(0.025)	(0.011)	(0.101)	(0.061)	(0.017)	(0.009)	(0.029)	(0.012)	(0.107)
# Days >3 SD Above mean	0.185	0.022	0.005	0.106	0.032	−0.089	0.002	−0.046	−0.019	−0.216*	−0.032	0.182
	(0.349)	(0.084)	(0.031)	(0.108)	(0.052)	(0.619)	(0.284)	(0.082)	(0.042)	(0.117)	(0.051)	(0.688)
Observations	185,892	185,892	185,892	185,892	185,892	176,734	180,373	180,373	180,373	180,373	180,373	170,707
R-squared	0.491	0.340	0.279	0.519	0.327	0.296	0.494	0.346	0.279	0.504	0.320	0.297
Adj. R^2	0.411	0.236	0.166	0.444	0.222	0.180	0.413	0.242	0.165	0.425	0.212	0.180
Mean	96.978	14.837	5.567	63.429	10.625	74.152	100.538	15.886	5.965	63.240	10.985	74.199

Notes: Each column reports regression coefficients (β_j) from Equation (1). Temperature bin -1SD to +1SD is omitted as a reference group. Robust standard errors, clustered by commuting zone, are in parentheses. High exposure groups are mothers whose pregnancies had greater overlap with summer months (i.e., births occurring July through December). Low exposure groups are mothers whose pregnancies had lower exposure to summer months (i.e., births occurring January through June). We use the data collapsed at the race×birth-county×birth-year-month level. Cell size weights are used.

*$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

Sources: GHCND weather data merged with U.S. National Vital Statistics Birth Data 2009–2018.

TABLE 5 Effects of absolute temperatures during pregnancy on birth outcomes, by race of mothers

		Number of births with adverse outcomes (in 1000 births)					
		Preterm birth	Very preterm birth	Extremely preterm birth	Low birthweight	Very low birthweight	NICU admission
# Days below 10F	Non-hispanic white	0.018	0.018	0.002	−0.005	−0.002	−0.03
		(0.04)	(0.01)	(0.008)	(0.03)	(0.01)	(0.06)
	Non-hispanic black	0.183	0.154***	0.049	0.253**	0.110***	0.214
		(0.14)	(0.05)	(0.039)	(0.11)	(0.04)	(0.19)
	Hispanic	0.201	0.004	−0.017	−0.012	−0.031	0.501**
		(0.14)	(0.05)	(0.028)	(0.11)	(0.04)	(0.20)
	Other	0.016	−0.034	−0.041	0.007	−0.076*	−0.037
		(0.14)	(0.06)	(0.033)	(0.12)	(0.04)	(0.25)
# Days 80–90F	Non-hispanic white	0.004	0.003	0.001	0.019*	0.003	−0.009
		(0.02)	(0.01)	(0.003)	(0.01)	(0.00)	(0.04)
	Non-hispanic black	0.024	0.015	0.009	0.049*	0.013	0.068
		(0.05)	(0.02)	(0.011)	(0.03)	(0.01)	(0.08)
	Hispanic	0.005	0.013	0.013**	0.015	0.017***	0.146
		(0.03)	(0.01)	(0.005)	(0.02)	(0.01)	(0.11)
	Other	−0.02	−0.007	−0.012	0.054	0.002	0.092
		(0.04)	(0.01)	(0.008)	(0.04)	(0.01)	(0.10)
# Days above 90F	Non-hispanic white	−0.003	0.016	0.014**	0.037	0.012	0.159**
		(0.03)	(0.01)	(0.006)	(0.02)	(0.01)	(0.06)
	Non-hispanic black	−0.003	0.094***	0.072***	−0.026	0.068**	0.115
		(0.08)	(0.04)	(0.024)	(0.07)	(0.03)	(0.13)
	Hispanic	−0.021	−0.006	0.010	−0.046	−0.007	0.235
		(0.06)	(0.02)	(0.010)	(0.05)	(0.01)	(0.18)
	Other	−0.126	0.005	−0.029	−0.01	−0.027	0.035
		(0.08)	(0.04)	(0.021)	(0.07)	(0.03)	(0.14)
N	Non-hispanic white	205,260	205,260	205,260	205,260	205,260	194,962
	Non-hispanic black	59,882	59,882	59,882	59,882	59,882	55,571
	Hispanic	67,181	67,181	67,181	67,181	67,181	64,413
	Other	33,942	33,942	33,942	33,942	33,942	32,495
Mean	Non-hispanic white	84.863	11.65	3.909	51.704	7.859	68.803
	Non-hispanic black	148.314	31.658	14.034	112.945	24.246	100.706
	Hispanic	103.351	14.864	5.415	58.928	9.949	71.961
	Other	87.534	11.73	4.081	65.984	8.545	69.249

Notes: The table reports regression coefficients (β_j) from Equation (1). Temperature bin of <10F, 80–90F, and >90F bins are shown—all other bins, except 60–70F bin, are included in the model, but not presented in the table. Robust standard errors, clustered by commuting zone, are in parentheses. We use the data collapsed at the race×birth-county×birth-year-month level. Cell size weights are used.

*$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

Sources: GHCND weather data merged with U.S. National Vital Statistics Birth Data 2009–2018.

An additional day of exposure to average temperatures between 80 and 90°F increases extremely preterm births and very low birthweight among only births to Hispanic mothers by about 0.2% of the sub-group mean for each outcome. It also appears to increase low birthweight among births to both non-Hispanic White and non-Hispanic Black mothers, with the effect sizes about 0.05% for each group.

An additional day of extreme heat with above 90°F average temperature increases very preterm births, extremely preterm births, and very low birthweight births among non-Hispanic Blacks by 0.5% for extremely preterm birth and by about 0.3% for the other two outcomes when evaluated at the sub-group mean. An additional day with above 90°F average temperature also increases extremely preterm births and NICU admissions among non-Hispanic Whites by 0.35% and 0.23% (of the sub-group mean), respectively. These results consistently show that the effect sizes for non-Hispanic Black and Hispanic mothers, while still small, are larger than the effect sizes we report for the overall sample and for the non-Hispanic White mothers.

5.1.4 | Effects of absolute temperatures during pregnancy on birth outcomes: By trimesters

As noted earlier, because we are using aggregated data at the mother's county-birth year-birth month-race group level, we define pregnancy period as the birth month and the prior 9-month period.[14] Hence, aggregated data inhibit identification and use of the exact pregnancy period and heat exposure for each birth. It also limits our ability to perform month- or trimester-of-pregnancy level analyses to pinpoint the vulnerable period of exposure. Nevertheless, we explore trimester-specific exposures by constructing time periods that correspond to trimesters of pregnancy relative to the month of birth assuming full gestation. We define birth month and the prior 2 months as the period that corresponds to the third trimester, three to 6 months prior to birth as the second trimester, and seven to 9 months prior to birth as the first trimester. In Table A4, we find that exposure to temperatures above 80°F in the first and third trimesters are most harmful for birthweight- and gestational age-related outcomes, while exposure to temperatures above 90°F in the second trimester is associated with increased likelihood of NICU admissions.

5.2 | Robustness check

5.2.1 | Robustness to different model specifications

We assess the robustness of our results to the choice of specification by including different combinations of fixed effects. The estimated coefficients across different specifications are shown in Table A5 where the last column in each sub-panel shows the results of our baseline specification given in Table 2, while other columns have the results by varying their coarseness—including less flexible models with fewer interaction fixed effects. Specifically, column (1) shows that our estimates from the main model stay robust for birthweight outcomes with county-by-year fixed effects and race-by-state-by-month fixed effects. Column (2) has county-by-month fixed effects, not interacted with race. In column (3), we include year fixed effects, not interacted with state fixed effects. All in all, the point estimates for the number of days with extreme temperatures are mostly similar across specifications, although differ in statistical significance for some outcomes, indicating that the results we present are not driven by the particular specification choice.[15]

5.2.2 | Robustness to placebo temperature exposures

We then run a series of falsification tests where we include placebo temperature exposures by including the number of days in various temperature bins in the 9-month intervals relative to (1) 24 months prior to the actual year-month of birth, (2) 12 months prior to the actual year-month of birth, and (3) 12 months after the actual year-month of birth. The results presented in Table A6–A8 indicate that the coefficients on placebo exposures to extreme temperatures are mostly insignificant or with opposite signs, and more importantly, our main treatment effects are not affected by inclusion of these placebo exposure variables.

5.2.3 | Robustness to relative temperature measures

The relative temperature measurement used so far is based on deviations from historic monthly average temperature and could overemphasize strange timing of exposure, not necessarily a measure of people being accustomed to a given temperature. Accordingly, we next measure "unexpectedness" using the *average over the year*, instead of historic mean for the month. Specifically, we create "hot-cutoffs" and "cold-cutoffs" for every county and year—"hot-cutoff" means the heat threshold a county experiences less than 10 days during a given year. For example, if Orange County experiences mean temperatures >100°F for 7 days, >99°F for 9 days, >98°F for 13 days during a given year, then the hot-cutoff for Orange county would be 99°F, indicating that if the number of days exposed to the certain temperature is less than 10 days annually, we argue that the residents in the county are not accustomed to that temperature, whichever month it takes place. Once we calculate these cutoffs, we count the number of days during pregnancy that exceeds a given hot- and cold-cutoff for all births occurring in each county, month, year. The average number of days during pregnancy with temperatures above the hot-cutoff is 6.2 days while the average number of days with temperatures below the cold-cutoff is 7.5 days.

Consistent with the findings above with the relative measure using standard deviations from the county-month mean, we find increases in preterm, very preterm births, and assisted ventilation associated with extremely cold temperatures in Table A9. The findings also indicate additional days with extremely high temperatures above the hot cutoff are associated with statistically significant increases in preterm and very preterm births, and gestational hypertension. The impacts on assisted ventilation and gestational hypertension appear to be more prominent among Black and Hispanic births (Table A10).

5.2.4 | Sensitivity to air quality control

Finally, we acknowledge that there is a well-established association between temperature and air quality and that air pollution is a potential confounding factor in the relationship between extreme temperature and health (Ye et al., 2012). Accordingly, we test the sensitivity of our findings to inclusion of controls for air quality measures for fine particulate matter (PM2.5) and ozone. We use Air Quality Index (AQI) data from the Environmental Protection Agency (EPA) which includes daily data identifying the average air quality in the county in one of the six AQI categories: good, moderate, unhealthy for sensitive groups, unhealthy, very unhealthy, and hazardous. Using these data, we construct county-year-month level data indicating the number of days in each county and each year and month with air quality falling in each of the six AQI categories from healthy to hazardous for either pollutant. Because the AQI data is available for relatively large counties with an air quality monitoring station nearby, which represents only about 53% of our sample, we run our main specification with and without the AQI variables for the sample for which the AQI data is available to show sensitivity of our results to inclusion of these variables. The results, given in Table A11, indicate that inclusion of AQI variables result in only minimal change in the estimated impact of extreme temperatures.[16]

6 | DISCUSSION

In this paper, we contribute to the understanding of the costs of exposure to extreme temperatures, by specifically studying the *in-utero* exposure to extreme temperatures and its impact on birth outcomes. Using the most recent national birth and weather data from 2009 to 2018, our estimates consistently point that an additional day with mean temperature greater than 80°F or less than 10°F adversely affects the infant's health at birth, by increasing preterm births and low birthweight. We further investigate the impact of *deviations* from the normal weather pattern, to identify the extreme weather events after accounting for the adaptation response. We find that extreme heat with temperatures two standard deviations above county's historic average induces preterm births and NICU admissions, particularly for mothers whose pregnancies greatly overlap with summer months. We also find that extreme cold with temperatures two standard deviations below the historic mean leads to the incidence of preterm births, regardless of whether the pregnancies overlap with winter or not.

Strikingly, the effects are far from equal across all mothers—the adverse effects are borne substantially more by Black and Hispanic mothers, which suggests that exposure to extreme temperatures may be a contributing factor for the birth-related health disparities across different race/ethnicity groups and may widen the gap further in the future as extreme temperatures become more common. The finding of a disproportionate impact is consistent with the recent literature that uncovered significant health disparities across the race/ethnicity groups in response to exposure to extreme temperatures (Barreca & Schaller, 2020; Deschenes et al., 2009; Kim et al., 2021). While it is important to consider the contribution of disproportionate impact of extreme temperatures to birth-related health disparities across different race/ethnicity groups, these differences likely account for a relatively small portion of *existing* racial/ethnic maternal health disparities when compared to societal factors such as income and education, or other environmental factors such as exposure to pollutants and toxic chemicals due to disproportional risk of exposure (Burris & Hacker, 2017).

Our effect sizes for gestational age- and birthweight-related outcomes associated with an additional day of extremely hot temperatures vary between 0.1 and 0.24%. These small but significant effects are consistent with the findings in the studies using birth certificate data from earlier years. In particular, Deschenes et al. (2009) find that an additional hot day with average temperature above 85°F (29.4°C) leads to 0.003–0.009% decline in birthweight in the U.S., and Hajdu & Hajdu, 2021 find that an additional day with average temperature above 25 °C (77°F) leads to 0.46 g (or 0.014%) decline in birthweight in Hungary. Similarly, Cil and Cameron (2017) find that heatwave exposure during pregnancy leads to a 2% of a week decrease in county average gestational age in the U.S. Chen et al. (2020), on the other hand, find somewhat larger effect sizes of 0.05% decrease in birthweight and about 1% of the mean increase in low birthweight associated with an additional day with mean temperatures above 28 °C (82.4°F) using Chinese birth data.

While we point to the consistency of our results with results in other studies, we are not able to directly compare the magnitudes of our estimates with those from past studies as they differ substantially along the dimension of temperature exposure measures, outcomes, and methodologies used. The comparison of our findings with that of other studies using data from other countries are further complicated by the differences across countries in terms of health care systems, recent temperature trends, culture and norm, adaptive behavior, and access to mitigation technologies. However, our paper manifests striking results that the adverse effects of extreme temperatures during pregnancy on infant's health *still exist* in the U.S., despite a widespread access to AC and adaptation to extreme weather over the past decade.

Aside from extreme temperature exposures, there are other risk factors to consider during pregnancy that could lead to adverse birth outcomes of infants, such as natural disasters (Currie & Rossin-Slater, 2013), air pollution (Bekkar et al., 2020), or grief due to a loss of family member (Persson & Rossin-Slater, 2018). These studies point to overall much larger effects on birth outcomes—about 11% increase in low birthweight or preterm birth in response to air pollution, 12% increase in low birthweight or preterm birth with exposure to stress due to the death of a family member. Yet, it is important to note that these events, while not rare, occur less frequently than increases in extreme temperatures taking place worldwide.

Small effect sizes and the counter-intuitive results for very low birthweight, should also be interpreted in the context of possible selection into live birth associated with extreme temperatures. Our estimates do not capture any potential adverse effect that prenatal exposure to extreme temperatures may have on fetal mortality as we only observe live births in the birth certificate data. Although we find no systematic change in racial/ethnic and educational composition of mothers in relation to extreme temperatures, which suggests that there is no differential selection into conception or live birth across different sociodemographic groups, it is still possible that exposure to extreme temperatures results in selection in utero across all groups. With selection in utero in response to a stressor, weaker fetuses select out of live birth and those survive to birth do not represent their conception cohort (Bruckner & Catalano, 2018). It is possible that we observe decrease in very low birthweight or only a small increase in other adverse outcomes in relation to extreme temperatures because those that would have otherwise been born with these adverse conditions select out of live birth. There is some evidence of increased stillbirths in relation to extreme temperatures (Asamoah et al., 2018; Chersich et al., 2020; Kanner et al., 2020; McElroy et al., 2022), and the possibility of observing positive associations between extreme temperatures and birth outcomes due to this potential *culling effect* has been discussed in other work (e.g., Chen et al., 2020).

We conduct a back-of-the-envelope calculation using 3.75 million births in 2019 (CDC Vital Statistics Rapid Release, May 2020) to offer future projections for an average American county. Our study suggests that one single additional day above 80°F during pregnancy is associated with 50 more infants with very preterm births and 100 more infants born with low birthweight, out of which 30 infants are born with very low birthweight. According to the recent climate change report, the number of days above 90°F is predicted to increase from one to 43 days per year by 2070–2099 (Intergovernmental Panel on Climate Change, 2014). With this dramatic increase in the frequency of hot days, the impact of in-utero exposures to extreme heat could have magnified effects over time, exacerbating the health disparities across racial/ethnicity groups at birth, which could carry over to one's life course.

7 | LIMITATIONS

Our study has several limitations. First, we are not able to pinpoint the exact timing or trimester of extreme temperature exposures that lead to adverse birth outcomes. The birth certificates collect information on the exact date of the last menstrual period, however, only the month and year are provided in the data. Furthermore, the endogeneity of the gestational age itself with respect to the in-utero shock further complicates using the actual gestational length in the analysis. Hence, we assume full pregnancy periods to assign prenatal exposures to extreme temperatures.

Second, we acknowledge that it would be useful to evaluate the mitigating role of air conditioning (AC) usage and assess the effects of extreme temperatures on the Black-White or Hispanic-White health gap in relation to racial/ethnic air conditioning (AC) share gap. AC usage is shown to be a protective factor significantly lowering the risk of heat-related health complications (Ostro et al., 2010). Moreover, a large proportion of racial disparities in heat-related mortality in late 1980 and 1990s is explained by the differences in prevalence of central AC (O'Neill et al., 2005). There are more recent studies providing evidence of persistent racial/ethnic disparities in access to air conditioning and the associated negative effects (Ito et al., 2018; Park et al., 2020). However, the lack of current AC data at county and month level, and for each racial/ethnic group prohibits us from exploring the adaptation behaviors. We note that one nationally available data on prevalence of air conditioning from Residential Energy Consumption Survey (RECS) identifies an air conditioning index at the state-year level for some states in some years in our study period. Yet we would need, at the minimum, a county-year level data on air conditioning to attempt disentangling the mitigating role of air conditioning because a state-year level variable on air conditioning would be subsumed by the state-year fixed effects in our main specification. A more geographically or temporally-refined data on air conditioning share, if exists, could potentially be used to test whether differential adoption of defensive investments by race/ethnicity groups might help explain the racial gap in infant health.

Finally, there may be other compensatory behavior to avoid exposure to extreme heat such as staying indoors on hot days (Moretti & Neidell, 2011; Neidell, 2009), and pregnant women may exhibit such behavior more compared to general population due to their more vulnerable state. This implies that even if we could isolate random variation in exposures to extreme temperature, if pregnant women have more propensity to adopt compensatory behaviors, the full effects of extreme temperatures will be understated. It is also possible that the racial/ethnic minorities and socio-economically disadvantaged groups have lower ability to adopt such avoidance behavior, for example, low-income women may not afford to stay home but have to work outside or work indoors with poor AC. Differential avoidance behavior across race/ethnicity groups may explain some of the observed differences in adverse effects of extreme temperatures by race/ethnicity. However, without data on individual behaviors, we are unable to identify the extent to which we are underestimating the effects of extreme heat on pregnant women generally, and to further explore racial/ethnic differences in avoidance behavior as a potential mechanism of differential impact.

8 | CONCLUSION

Nearly all scientists agree that the world is going to be considerably warmer in a few decades, with a gradual rightward shift of the entire temperature distribution, causing more frequent extreme weather events, such as heat waves, wildfire, rainstorms, and droughts. Big cities in the U.S. are expected to see both their summer and winter temperature shift by more than 3°F on average by 2050 (Vox, 2019). Therefore, understanding the economic costs and potential benefits of mitigating policies is central in informing discussions about consequences of climate changes on human beings.

Our study is the *first* to use the universe of U.S. birth data from 2009 through 2018 to provide up-to-date estimates of the impact of prenatal exposures to extreme temperatures on birth outcomes. We believe it is pivotal to update and expand the studies for every decade, given the rapidly increasing ambient temperatures worldwide as well as more frequent extreme weather events, to understand its economic costs by evaluating its impact on health at birth—the very first starting point of one's life.

ACKNOWLEDGMENTS

None of the authors have received financial support. None of the authors held any paid or unpaid positions as officer, director, or board member of relevant nonprofit organizations or profit-making entities.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

This study uses restricted-use data from the National Vital Statistics System Natality Detail Files. The data can be obtained by filing a request directly with the National Center for Health Statistics (https://www.cdc.gov/nchs/nvss/births.htm).

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ENDNOTES

[1] Fahrenheit to Celsius conversion formula is (°F−32)/1.8 = °C.

[2] The national birth data from 1972 to 1988 include exact date of birth, which allows researchers to calculate the exact gestational ages and trimesters. This variable was no longer made publicly available starting from 1989.

[3] This is to continue to investigate racial disparity in health, following Deschenes et al. (2009). However, Deschenes et al. (2009) examines only by Whites/Blacks. We expand the race categories to include Hispanic and other races.

[4] The variable definitions for each of the birthweight- and gestational age-related outcomes (1)-(5) are applied to the same group of births separately. For example, very preterm births are a sub-group of preterm births, and preterm and very preterm births are not mutually exclusive groups. Outcome (6) is an intersection of (1) and (4).

[5] In many relevant papers, station-level weather data are aggregated at the county level by taking an inverse-distance from stations that are located within a certain distance (radius) of each county's centroid (Deschenes et al., 2009). In this study, we simply take the average of all the stations in a given county.

[6] We further use the GHCND weather data for years 2006–2008 and 2019 for placebo temperature tests.

[7] The birth certificate data collects information on the gestational age, however, we do not utilize this measure to identify heat exposure period based on month of conception because we collapse our national birth data into cells at county, birth year-month, and race levels. Moreover, gestational age itself may be an outcome of exposure to extreme temperatures (Currie & Rossin-Slater, 2013; Deschenes et al., 2009).

[8] Our sample shows that about 45% of newborns had gestational age of 38 or 39 weeks, 20% of newborns had 40 weeks, and about 13% of newborns had greater than 40 weeks. If we instrument actual exposure by counting 40 weeks *forward* from *conception month*, then measurement errors will be introduced during the last weeks of pregnancy for those who give birth earlier than due date. The exposure during second and third trimester has been documented to have stronger effects than first trimester (Deschenes et al., 2009, Barreca & Schaller, 2020). Hence, cost of misplacing temperature exposure during the last weeks of pregnancy is potentially greater than misplacing exposure during the first weeks of pregnancy.

[9] Each Fahrenheit temperature bin corresponds to the following Celsius bins: <-12.2, −12.2 to −6.7, −6.7 to −1.1, −1.1–4.4, 4.4–10, 10–15.6, 15.6–21.1, 21.1–26.7, 26.7–32.2, and >32.2°C.

[10] Previous studies in the economic literature find that adverse effects of heat are more pronounced if it occurs during the second and third trimester (Barreca & Schaller, 2020; Deschenes et al., 2009). Accordingly, we classify pregnancy to be "Low exposure" if there is no overlap with summer months or if it partly overlaps with summer months during the first trimester. "High exposure" pregnancies have exposure to summer months during the second and/or third trimesters.

[11] Information on NICU admission is collected only in the revised version of the birth certificate issued by U.S. Department of Health and Human Services in 2003 and adopted by the states gradually in the following several years. In the first year our study period, 2009, there were a total of 31 states and Washington D.C. using the revised version, and all of the states adopted the revised birth certificate by 2016. Accordingly, NICU variable is not available for a number of states in the first few years in our data reducing the sample size for this outcome.

[12] We are unable to control for mother's cohabitation or domestic partnership status as the birth certificate data do not include any information on these variables. When we add a binary control variable indicating father's presence on the birth certificate as a proxy for cohabitation/domestic partnership, our results do not change.

[13] With potential spatial autocorrelation across counties at the state borders in mind, we tried two-way clustering at the commuting zone-year level, as well as the commuting zone-month level, and found that the results are substantially similar.

[14] When we try defining pregnancy period as the birth month and the prior 8-month period to address the concerns about selection into fertility, the results are substantially similar and, in some cases, they suggest larger or more significant effect sizes. Results are available upon request.

[15] We also run our main model specification by dropping the mother's demographic controls and the estimates are nearly identical to those from the main specification. Results not shown in Appendix Table A5; available upon request.

[16] We acknowledge that the effects of air pollution on pregnant women may vary by the nature of the exposure (acute vs. lasting) and the pollutant type, and that our air quality variable is a crude measure of pollution exposure. We also note that studying the effects of air pollution, or the interactive effects of air pollution and temperature is not within the scope of this study, and that our goal is merely to assess the sensitivity of our findings for extreme temperature exposure to possible confounding by air pollution.

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How to cite this article: Cil, G., & Kim, J. (2022). Extreme temperatures during pregnancy and adverse birth outcomes: Evidence from 2009 to 2018 U.S. national birth data. *Health Economics*, 1–32. https://doi.org/10.1002/hec.4559

APPENDIX A

TABLE A1 Summary statistics by different subgroups

Average number of days during pregnancy with mean temperature	All mothers	High exposure	Low exposure	Non-hispanic white	Non-hispanic black	Hispanic	Other
Relative							
>3SDs below mean	0.594	0.592	0.596	0.548	0.633	0.722	0.429
2–3 SDs below mean	7.229	7.117	7.348	7.173	7.568	7.384	6.398
2–3 SDs above mean	5.094	5.172	5.01	5.128	4.77	4.89	6.251
>3SDs above the mean	0.194	0.206	0.181	0.163	0.126	0.244	0.407
Absolute							
<10F degrees	2.474	2.156	2.812	3.462	1.576	0.941	1.89
10–20F degrees	5.872	5.187	6.599	7.711	4.626	2.866	4.427
80–90F degrees	31.065	34.178	27.761	24.366	39.958	43.143	22.873
>90F degrees	1.992	2.228	1.742	1.407	1.281	3.775	1.85

Notes: High exposure groups are mothers whose pregnancies had greater overlap with summer months (i.e., births occurring July through December). Low exposure groups are mothers whose pregnancies had lower exposure to summer months (i.e., births occurring January through June).

Sources: GHCND weather data merged with U.S. National Vital Statistics Birth Data 2009–2018.

TABLE A2 Effects of relative temperatures during pregnancy on mother's demographic characteristics

	Race/Ethnicity				Education				Marital status
	Non-hisp. White	Non-hisp. Black	Hispanic	Other	Less than high school	High school	Some college	College or more	Married
# Days below 10F	0.169	−0.027	−0.072	−0.069	−0.02	−0.064	0.078	0.006	−0.169
	(0.112)	(0.072)	(0.085)	(0.087)	(0.087)	(0.085)	(0.091)	(0.102)	(0.124)
# Days 10–20F	−0.05	−0.026	0.063	0.012	−0.006	0.146	−0.093	−0.047	−0.109
	(0.072)	(0.062)	(0.063)	(0.079)	(0.087)	(0.101)	(0.095)	(0.096)	(0.120)
# Days 20–30F	−0.001	0.055	−0.016	−0.038	−0.007	−0.025	−0.083	0.115	−0.136
	(0.053)	(0.048)	(0.057)	(0.057)	(0.049)	(0.070)	(0.068)	(0.075)	(0.097)
# Days 30–40F	0.043	−0.073**	0.019	0.011	0.027	0.068	0.008	−0.103*	−0.138
	(0.039)	(0.035)	(0.039)	(0.041)	(0.043)	(0.056)	(0.056)	(0.062)	(0.109)
# Days 40–50F	0.008	0.005	−0.002	−0.01	0.027	0.061	−0.052	−0.036	−0.052
	(0.026)	(0.027)	(0.030)	(0.031)	(0.037)	(0.048)	(0.058)	(0.044)	(0.082)
# Days 50–60F	−0.004	−0.017	0.017	0.004	−0.049	0.05	0.080**	−0.082*	−0.216
	(0.023)	(0.023)	(0.026)	(0.026)	(0.044)	(0.041)	(0.040)	(0.043)	(0.220)
# Days 70–80F	−0.022	0.022	−0.014	0.014	0.003	−0.016	−0.02	0.034	0.011
	(0.021)	(0.019)	(0.027)	(0.023)	(0.027)	(0.026)	(0.030)	(0.034)	(0.050)
# Days 80–90F	0.009	0.003	−0.018	0.005	0.021	−0.049	−0.054	0.082	0.087
	(0.029)	(0.024)	(0.033)	(0.037)	(0.038)	(0.037)	(0.067)	(0.062)	(0.056)
# Days above 90F	−0.033	−0.019	0.066	−0.014	−0.031	−0.118	0.179	−0.03	−0.27
	(0.064)	(0.044)	(0.064)	(0.085)	(0.088)	(0.090)	(0.166)	(0.104)	(0.185)
Observations	219,699	219,699	219,699	219,699	214,995	214,995	214,995	214,995	219,051
R-squared	0.932	0.858	0.828	0.856	0.691	0.596	0.542	0.824	0.713
Adj. R-squared	0.922	0.838	0.803	0.835	0.645	0.537	0.475	0.798	0.672
Mean	387.428	210.324	228.764	173.483	164.957	252.917	276.086	306.04	588.427

TABLE A2 (Continued)

	Race/Ethnicity				Education				Marital status
	Non-hisp. White	Non-hisp black	Hispanic	Other	Less than high school	High school	Some college	College or more	Married
# Days >3 SD below mean	−8.015**	2.448	4.928	0.639	0.527	0.006	−3.442*	2.909	2.318
	(4.046)	(2.205)	(4.042)	(1.669)	(1.994)	(2.044)	(1.816)	(2.311)	(1.895)
# Days 2-3 SD below mean	0.45	−0.838	0.182	0.206	0.279	−0.369	0.602	−0.512	−0.807*
	(0.338)	(0.510)	(0.410)	(0.232)	(0.326)	(0.384)	(0.588)	(0.446)	(0.445)
# Days 1-2 SD below mean	−0.012	−0.099	0.116	−0.004	−0.055	−0.17	0.033	0.192	0.077
	(0.177)	(0.225)	(0.196)	(0.113)	(0.120)	(0.151)	(0.127)	(0.209)	(0.116)
# Days 1-2 SD above mean	0.011	−0.052	0.144	−0.103	0.11	−0.053	−0.034	−0.022	−0.218*
	(0.119)	(0.124)	(0.120)	(0.091)	(0.107)	(0.166)	(0.119)	(0.188)	(0.114)
# Days 1-2 SD above mean	−0.372	−0.693	0.785	0.28	−0.008	−1.832***	0.082	1.757	−0.17
	(0.599)	(0.884)	(0.571)	(0.366)	(0.930)	(0.704)	(0.367)	(1.546)	(0.545)
# Days >3 SD above mean	1.39	3.786	−5.622	0.446	1.686	−4.956	3.822	−0.552	−2.236
	(2.209)	(2.661)	(4.445)	(1.378)	(2.140)	(3.121)	(2.471)	(4.998)	(2.519)
Observations	219,699	219,699	219,699	219,699	214,995	214,995	214,995	214,995	219,051
R-squared	0.932	0.858	0.828	0.856	0.691	0.596	0.542	0.824	0.713
Adj. R-squared	0.922	0.838	0.803	0.835	0.645	0.537	0.475	0.798	0.672
Mean	387.428	210.324	228.764	173.483	164.957	252.917	276.086	306.04	588.427

Notes: Each column reports regression coefficients (β_j) from equation 1. Temperature bin -1SD to +1SD is omitted as a reference group. Robust standard errors, clustered by commuting zone, are in parentheses. We no longer control for X_{rcym} in the model as they are the outcome variables. We use the data collapsed at the birth-county×birth-year-month level. Cell size weights are used.

*$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

Sources: GHCND weather data merged with U.S. National Vital Statistics Birth Data 2009–2018.

TABLE A3 Effects of extreme temperatures during pregnancy on additional birth outcomes

	Number of births with adverse outcomes (in 1000 births)		
	# Required assisted ventilation	Gestational hypertension	Pre-term and low birth weight
Panel A: Effects of absolute temperatures			
# Days below 10F	0.028	−0.006	0.024
	(0.09)	(0.04)	(0.020)
# Days 10–20F	0.019	−0.003	−0.017
	(0.06)	(0.04)	(0.016)
# Days 20–30F	0.066	0.055**	0.016
	(0.06)	(0.03)	(0.013)
# Days 30–40F	0.014	0.032*	0.001
	(0.04)	(0.02)	(0.009)
# Days 40–50F	−0.009	0.041**	0.009
	(0.04)	(0.02)	(0.007)
# Days 50–60F	0.034	0.031**	0.007
	(0.04)	(0.02)	(0.006)
# Days 70–80F	0.026	0.014	0.012**
	(0.02)	(0.01)	(0.005)
# Days 80–90F	0.071	−0.026	0.010
	(0.05)	(0.02)	(0.008)

(Continues)

TABLE A3 (Continued)

	Number of births with adverse outcomes (in 1000 births)		
	# Required assisted ventilation	Gestational hypertension	Pre-term and low birth weight
# Days above 90F	−0.005	0.031	−0.005
	(0.11)	(0.04)	(0.019)
R-squared	0.34	0.46	0.418
Adjusted R-squared	0.235	0.376	0.327
Panel B: Effects of relative temperatures			
# Days >3 SD below mean	−0.056	0.052	−0.045
	(0.06)	(0.15)	(0.059)
# Days 2-3 SD below mean	0.007	0.02	0.022
	(0.02)	(0.04)	(0.015)
# Days 1-2 SD below mean	0.014	0.016	0.002
	(0.01)	(0.02)	(0.007)
# Days 1-2 SD above mean	0.009	−0.015	0.008
	(0.01)	(0.02)	(0.007)
# Days 2-3 SD above mean	−0.040*	0.07	−0.000
	(0.02)	(0.05)	(0.016)
# Days >3 SD above mean	0.049	0.196	−0.009
	(0.11)	(0.29)	(0.054)
R-squared	0.34	0.46	0.418
Adjusted R-squared	0.235	0.376	0.327
Observations	347,441	366,231	366,265
Mean	34.75	50.35	38.911

Notes: Each column reports regression coefficients (β_j) from Equation (1). Panel A: Temperature bin 60–70F is omitted as a reference group. Robust standard errors, clustered by commuting zone, are in parentheses. Panel B: Temperature bin -1SD to +1SD is omitted as a reference group. We use the data collapsed at the race×birth-county×birth-year-month level. Cell size weights are used.

*$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

Sources: GHCND weather data merged with U.S. National Vital Statistics Birth Data 2009–2018.

TABLE A4 Effects of absolute temperatures during pregnancy on birth outcomes: By trimesters

			Number of births with adverse outcomes (in 1000 births)				
		Preterm birth	Very preterm birth	Extremely preterm birth	Low birthweight	Very low birthweight	NICU admission
Trimester 1	# Days below 10F	0.091	0.049***	0.012	0.05	0.016	0.078
		(0.057)	(0.018)	(0.011)	(0.036)	(0.015)	(0.091)
	# Days 10–20F	0.063	0.008	−0.009	0.054*	−0.002	−0.021
		(0.042)	(0.017)	(0.008)	(0.028)	(0.011)	(0.117)
	# Days 20–30F	0.041	0.008	0.014**	0.015	0.01	−0.203***
		(0.033)	(0.013)	(0.006)	(0.021)	(0.008)	(0.074)
	# Days 30–40F	0.028	−0.001	0.003	0.025	−0.003	−0.021
		(0.027)	(0.010)	(0.005)	(0.017)	(0.006)	(0.069)
	# Days 40–50F	0.008	0.001	0.005	0.035**	0.004	−0.002
		(0.025)	(0.007)	(0.004)	(0.016)	(0.006)	(0.043)
	# Days 50–60F	0.02	0.002	0.007**	0.003	0.002	−0.111*
		(0.019)	(0.006)	(0.004)	(0.011)	(0.005)	(0.066)

TABLE A4 (Continued)

		Number of births with adverse outcomes (in 1000 births)					
		Preterm birth	Very preterm birth	Extremely preterm birth	Low birthweight	Very low birthweight	NICU admission
	# Days 70–80F	0.008	0.009	0.006**	0.011	0.005	−0.016
		(0.021)	(0.006)	(0.003)	(0.015)	(0.005)	(0.032)
	# Days 80–90F	0.011	0.018**	0.009*	0.023	0.016**	0.076
		(0.028)	(0.009)	(0.005)	(0.018)	(0.006)	(0.085)
	# Days above 90F	0.058	0.036***	0.021***	0.02	0.028**	0.202
		(0.050)	(0.014)	(0.008)	(0.033)	(0.011)	(0.123)
Trimester 2	# Days below 10F	0.035	0.022	0.004	−0.011	−0.004	−0.058
		(0.044)	(0.015)	(0.008)	(0.030)	(0.011)	(0.081)
	# Days 10–20F	0.014	0.001	0.003	0.006	0.003	0.046
		(0.036)	(0.014)	(0.008)	(0.028)	(0.010)	(0.090)
	# Days 20–30F	0.046	0.003	0.007	0.018	0.009	−0.085
		(0.031)	(0.011)	(0.005)	(0.019)	(0.007)	(0.066)
	# Days 30–40F	0.008	−0.005	0.002	0.01	−0.001	−0.075
		(0.024)	(0.009)	(0.005)	(0.016)	(0.007)	(0.046)
	# Days 40–50F	0.014	0	−0.002	0.009	−0.007	−0.044
		(0.022)	(0.006)	(0.004)	(0.012)	(0.005)	(0.037)
	# Days 50–60F	0.022	−0.002	0.002	0.019**	0.003	0.105
		(0.018)	(0.006)	(0.003)	(0.009)	(0.004)	(0.081)
	# Days 70–80F	0.029**	−0.003	−0.001	0.006	−0.001	0.044
		(0.014)	(0.005)	(0.003)	(0.009)	(0.004)	(0.032)
	# Days 80–90F	−0.01	−0.005	−0.001	0.02	0.002	0.085
		(0.022)	(0.007)	(0.003)	(0.012)	(0.005)	(0.054)
	# Days above 90F	−0.041	−0.014	0.005	−0.031	−0.013	0.193*
		(0.042)	(0.011)	(0.006)	(0.030)	(0.009)	(0.108)
Trimester 3	# Days below 10F	0.071	0.033*	0.002	0.056	0.008	0.166
		(0.055)	(0.018)	(0.011)	(0.034)	(0.014)	(0.105)
	# Days 10–20F	0.006	−0.024	−0.013	−0.059*	−0.023*	−0.008
		(0.046)	(0.016)	(0.010)	(0.033)	(0.013)	(0.121)
	# Days 20–30F	0.073*	−0.007	−0.003	0.031	0.003	0.133
		(0.039)	(0.011)	(0.006)	(0.024)	(0.009)	(0.107)
	# Days 30–40F	0.025	−0.015*	−0.007	0.002	−0.014**	0.013
		(0.027)	(0.009)	(0.005)	(0.015)	(0.006)	(0.075)
	# Days 40–50F	0.051**	0.007	0.002	0.018	−0.002	0.092
		(0.024)	(0.008)	(0.004)	(0.015)	(0.007)	(0.090)
	# Days 50–60F	0.007	−0.002	0.001	−0.009	−0.002	0.014
		(0.021)	(0.007)	(0.004)	(0.012)	(0.005)	(0.043)
	# Days 70–80F	0.039*	0.007	0.004	0.017	0.004	0.006
		(0.022)	(0.007)	(0.003)	(0.011)	(0.004)	(0.035)
	# Days 80–90F	0.028	0.008	0.004	0.040***	0.009	−0.029
		(0.026)	(0.008)	(0.004)	(0.014)	(0.006)	(0.044)
	# Days above 90F	−0.059	0.025**	0.018**	0.006	0.011	0.036
		(0.063)	(0.012)	(0.007)	(0.029)	(0.010)	(0.081)
Observations		366,265	366,265	366,265	366,265	366,265	347,441
R-squared		0.492	0.342	0.278	0.511	0.323	0.288
Adj. R-squared		0.413	0.24	0.166	0.435	0.217	0.171
Mean		98.706	15.346	5.760	63.337	10.799	74.175

Notes: Each column in each trimester reports regression coefficients (β_j) from Equation (1). Temperature bin 60–70F is omitted as a reference group. Robust standard errors, clustered by commuting zone, are in parentheses. We use the data collapsed at the race×birth-county×birth-year-month level. Cell size weights are used.

*$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

Sources: GHCND weather data merged with U.S. National Vital Statistics Birth Data 2009–2018.

TABLE A5 Effects of absolute temperatures during pregnancy on birth outcomes: Specification checks

	Number of births with adverse outcomes (in 1000 births)											
	Preterm birth				Very preterm birth				Extremely preterm birth			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
# Days below 10F	0.056	0.04	0.090**	0.055	0.008	0.023*	0.005	0.028**	−0.012	0.002	−0.002	0.005
	(0.038)	(0.037)	(0.036)	(0.038)	(0.018)	(0.013)	(0.009)	(0.013)	(0.009)	(0.007)	(0.005)	(0.007)
# Days 10–20F	−0.034	0.007	0.051	0.021	−0.020	−0.012	−0.004	−0.008	−0.002	−0.010*	−0.008*	−0.006
	(0.033)	(0.029)	(0.033)	(0.027)	(0.014)	(0.012)	(0.009)	(0.012)	(0.008)	(0.006)	(0.004)	(0.006)
# Days 20–30F	0.000	0.036	0.069***	0.052**	−0.002	−0.006	0.005	0.000	−0.005	0.003	0.006*	0.006
	(0.026)	(0.025)	(0.025)	(0.024)	(0.009)	(0.009)	(0.006)	(0.009)	(0.005)	(0.004)	(0.003)	(0.004)
# Days 30–40F	−0.002	0.001	0.046**	0.019	−0.007	−0.014**	−0.007	−0.007	0.000	−0.004	−0.003	−0.000
	(0.022)	(0.020)	(0.022)	(0.019)	(0.007)	(0.007)	(0.006)	(0.007)	(0.004)	(0.003)	(0.003)	(0.003)
# Days 40–50F	−0.008	0.012	0.056**	0.025	−0.003	−0.001	0.008*	0.003	−0.001	−0.001	0.000	0.001
	(0.015)	(0.018)	(0.026)	(0.017)	(0.005)	(0.005)	(0.005)	(0.005)	(0.003)	(0.003)	(0.002)	(0.003)
# Days 50–60F	−0.010	−0.005	0.060**	0.016	−0.003	−0.008	0.001	−0.001	0.001	−0.000	0.001	0.003
	(0.012)	(0.018)	(0.024)	(0.014)	(0.005)	(0.005)	(0.006)	(0.004)	(0.002)	(0.002)	(0.003)	(0.002)
# Days 70–80F	−0.005	0.025**	0.027**	0.024**	0.002	0.003	0.000	0.003	0.002	0.003*	0.001	0.003*
	(0.010)	(0.012)	(0.011)	(0.012)	(0.003)	(0.003)	(0.003)	(0.003)	(0.002)	(0.002)	(0.002)	(0.002)
# Days 80–90F	−0.010	0.01	−0.008	0.006	0.004	0.007	0.004	0.006	0.004	0.005*	0.004*	0.004
	(0.013)	(0.018)	(0.020)	(0.018)	(0.004)	(0.004)	(0.004)	(0.005)	(0.002)	(0.003)	(0.002)	(0.003)
# Days above 90F	−0.033	−0.049	−0.046	−0.02	0.007	0.003	0.007	0.013*	0.004	0.009	0.010***	0.014***
	(0.028)	(0.034)	(0.033)	(0.033)	(0.008)	(0.009)	(0.008)	(0.007)	(0.005)	(0.005)	(0.004)	(0.004)
year FE			X				X				X	
county*year FE	X				X				X			
state*year FE		X		X		X		X		X		X
county*month FE		X				X				X		
race*state*month FE	X				X				X			
race*county*month FE			X	X			X	X			X	X
Observations	366,265	366,083	366,083	366,265	366,265	366,083	366,083	366,265	366,265	366,265	366,265	366,265
R-squared	0.467	0.408	0.488	0.492	0.287	0.25	0.34	0.342	0.212	0.184	0.277	0.278
Adj. R-squared	0.430	0.359	0.409	0.413	0.237	0.189	0.238	0.24	0.157	0.118	0.165	0.166
Mean	98.706	98.706	98.706	98.706	15.346	15.346	15.346	15.346	5.760	5.760	5.760	5.760

TABLE A5 (Continued)

	Number of births with adverse outcomes (in 1000 births)											
	Low birthweight				Very low birthweight				NICU admission			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
# Days below 10F	0.035	−0.005	0.021	0.017	−0.009	−0.002	−0.005	0.003	0.100	0.021	0.119	0.029
	(0.033)	(0.026)	(0.015)	(0.026)	(0.014)	(0.009)	(0.006)	(0.009)	(0.076)	(0.061)	(0.118)	(0.063)
# Days 10–20F	−0.081**	−0.02	−0.012	−0.006	−0.016	−0.013*	−0.015***	−0.008	−0.102	−0.005	0.053	−0.001
	(0.035)	(0.021)	(0.015)	(0.020)	(0.011)	(0.008)	(0.005)	(0.008)	(0.093)	(0.077)	(0.113)	(0.078)
# Days 20–30F	−0.000	−0.002	0.006	0.019	−0.002	0.001	0.004	0.006	0.077	−0.056	−0.084	−0.05
	(0.021)	(0.017)	(0.011)	(0.015)	(0.007)	(0.005)	(0.004)	(0.005)	(0.078)	(0.055)	(0.061)	(0.056)
# Days 30–40F	−0.003	−0.008	−0.003	0.012	−0.006	−0.011**	−0.010***	−0.006	−0.048	−0.037	0.015	−0.03
	(0.014)	(0.012)	(0.008)	(0.011)	(0.005)	(0.004)	(0.003)	(0.004)	(0.039)	(0.039)	(0.063)	(0.041)
# Days 40–50F	−0.008	0.005	0.006	0.020**	−0.006	−0.006	−0.004	−0.002	0.018	0.008	−0.022	0.013
	(0.010)	(0.012)	(0.008)	(0.010)	(0.004)	(0.004)	(0.003)	(0.003)	(0.030)	(0.033)	(0.055)	(0.034)
# Days 50–60F	−0.011	−0.015	0.003	0.005	0.000	−0.004	−0.003	0.002	0.016	−0.001	0.046	0.008
	(0.008)	(0.013)	(0.006)	(0.006)	(0.004)	(0.003)	(0.003)	(0.003)	(0.028)	(0.034)	(0.107)	(0.039)
# Days 70–80F	0.002	0.01	0.008	0.01	0.000	0.002	0.001	0.002	0.005	0.009	0.018	0.013
	(0.006)	(0.008)	(0.006)	(0.007)	(0.002)	(0.002)	(0.002)	(0.002)	(0.017)	(0.019)	(0.038)	(0.020)
# Days 80–90F	0.013*	0.028***	0.028***	0.026***	0.006*	0.009**	0.005*	0.008**	0.033	0.04	0.080*	0.042
	(0.008)	(0.009)	(0.008)	(0.009)	(0.003)	(0.003)	(0.003)	(0.004)	(0.043)	(0.044)	(0.046)	(0.046)
# Days above 90F	−0.011	−0.039	0.032**	−0.006	0.002	−0.003	0.002	0.007	0.100	0.121	0.095	0.153*
	(0.016)	(0.025)	(0.016)	(0.024)	(0.005)	(0.008)	(0.006)	(0.006)	(0.070)	(0.094)	(0.079)	(0.092)
year FE			X				X				X	
county*year FE	X				X				X			
state*year FE		X		X		X		X		X		X
county*month FE		X				X				X		
race*state*month FE	X				X				X			
race*county*month FE			X	X			X	X			X	X
Observations	366,265	366,083	366,083	366,265	366,265	366,083	366,083	366,265	347,441	347,259	347,259	347,441
R-squared	0.464	0.361	0.51	0.511	0.261	0.219	0.322	0.323	0.301	0.222	0.257	0.287
Adj. R-squared	0.427	0.309	0.434	0.435	0.209	0.155	0.217	0.217	0.251	0.155	0.137	0.17
Mean	63.337	63.337	63.337	63.337	10.799	10.799	10.799	10.799	74.175	74.175	74.175	74.175

TABLE A6 Effects of absolute temperatures during pregnancy on birth outcomes: placebo temperatures assuming counterfactual birth date—two years prior to the actual birth year-month

	Number of births with adverse outcomes (in 1000 births)											
	Preterm birth		**Very preterm birth**		**Extremely preterm birth**		**Low birthweight**		**Very low birthweight**		**NICU admission**	
# Days below 10F	0.004	0.019	−0.011	−0.004	0.009	0.010	−0.02	−0.028	0.001	0.001	0.03	0.063
- 2 years lag	(0.036)	(0.042)	(0.014)	(0.015)	(0.008)	(0.008)	(0.028)	(0.031)	(0.011)	(0.011)	(0.073)	(0.086)
# Days 10–20F	−0.009	−0.005	−0.015	−0.015	−0.005	−0.008	0.005	−0.001	−0.005	−0.007	0.035	0.041
- 2 years lag	(0.034)	(0.035)	(0.011)	(0.011)	(0.006)	(0.006)	(0.021)	(0.021)	(0.008)	(0.008)	(0.081)	(0.087)
# Days 20–30F	0.02	0.029	0.008	0.007	0.007	0.006	0.005	0.000	0.003	0.002	−0.049	−0.07
- 2 years lag	(0.025)	(0.026)	(0.008)	(0.009)	(0.004)	(0.004)	(0.014)	(0.015)	(0.006)	(0.006)	(0.051)	(0.055)
# Days 30–40F	−0.002	0.000	0.000	−0.002	0.004	0.003	−0.004	−0.006	0.001	−0.001	−0.038	−0.056
- 2 years lag	(0.021)	(0.020)	(0.006)	(0.006)	(0.003)	(0.003)	(0.012)	(0.012)	(0.004)	(0.004)	(0.039)	(0.041)
# Days 40–50F	0.000	0.001	−0.001	0.000	0.003	0.003	0.003	0.002	−0.001	−0.002	0.038	0.042
- 2 years lag	(0.019)	(0.020)	(0.005)	(0.005)	(0.003)	(0.003)	(0.009)	(0.009)	(0.003)	(0.004)	(0.046)	(0.050)
# Days 50–60F	−0.006	−0.004	−0.001	−0.002	0.004*	0.004**	0.004	0.003	0.003	0.002	−0.008	−0.014
- 2 years lag	(0.014)	(0.014)	(0.004)	(0.004)	(0.002)	(0.002)	(0.007)	(0.008)	(0.003)	(0.003)	(0.041)	(0.043)
# Days 70–80F	−0.027**	−0.024*	−0.004	−0.004	0.001	0.002	−0.002	−0.001	−0.001	−0.001	−0.004	−0.002
- 2 years lag	(0.012)	(0.013)	(0.003)	(0.003)	(0.002)	(0.002)	(0.006)	(0.006)	(0.002)	(0.002)	(0.028)	(0.028)
# Days 80–90F	−0.040**	−0.042**	−0.007	−0.006	−0.004	−0.003	−0.002	0.000	−0.003	−0.003	0.05	0.063
- 2 years lag	(0.017)	(0.018)	(0.005)	(0.005)	(0.003)	(0.003)	(0.010)	(0.010)	(0.004)	(0.004)	(0.047)	(0.050)
# Days above 90F	0.037	0.034	0.009	0.01	0.007	0.007	0.013	0.013	0.001	0.001	−0.006	0.002
- 2 years lag	(0.026)	(0.025)	(0.009)	(0.009)	(0.005)	(0.005)	(0.022)	(0.021)	(0.007)	(0.007)	(0.065)	(0.067)
# Days below 10F		0.05		0.022*		0.006		0.002		0.001		0.106
		(0.046)		(0.013)		(0.007)		(0.028)		(0.010)		(0.081)
# Days 10–20F		0.03		−0.008		−0.006		−0.006		−0.009		−0.006
		(0.029)		(0.012)		(0.006)		(0.021)		(0.008)		(0.086)
# Days 20–30F		0.051**		0.000		0.008**		0.012		0.007		−0.06
		(0.024)		(0.008)		(0.004)		(0.015)		(0.005)		(0.061)
# Days 30–40F		0.014		−0.009		0.001		0.009		−0.006		−0.039
		(0.020)		(0.007)		(0.004)		(0.011)		(0.004)		(0.045)
# Days 40–50F		0.022		0.003		0.002		0.019*		−0.002		0.017
		(0.018)		(0.005)		(0.003)		(0.010)		(0.004)		(0.040)
# Days 50–60F		0.011		−0.002		0.005**		0.003		0.001		0.012
		(0.014)		(0.004)		(0.003)		(0.007)		(0.003)		(0.042)

TABLE A6 (Continued)

	Number of births with adverse outcomes (in 1000 births)											
	Preterm birth		Very preterm birth		Extremely preterm birth		Low birthweight		Very low birthweight		NICU admission	
# Days 70–80F		0.021*		0.003		0.004**		0.009		0.002		0.008
		(0.013)		(0.004)		(0.002)		(0.007)		(0.002)		(0.021)
# Days 80–90F		−0.002		0.005		0.004		0.025***		0.007**		0.052
		(0.019)		(0.005)		(0.003)		(0.009)		(0.004)		(0.050)
# Days above 90F		−0.036		0.011		0.014***		−0.007		0.006		0.178*
		(0.034)		(0.007)		(0.004)		(0.024)		(0.006)		(0.101)
Observations	358,833	358,833	358,833	358,833	330,767	330,767	358,833	358,833	358,833	358,833	340,563	340,563
R-squared	0.496	0.496	0.346	0.346	0.288	0.288	0.515	0.515	0.326	0.326	0.289	0.289
Adj. R-squared	0.416	0.416	0.242	0.242	0.166	0.166	0.438	0.438	0.219	0.219	0.171	0.171
Mean	98.706	98.706	15.346	15.346	5.760	5.760	63.337	63.337	10.799	10.799	74.175	74.175

Notes: Each column reports regression coefficients (β_j) from equation 1. Temperature bin 60–70F is omitted as a reference group. Robust standard errors, clustered by commuting zone, are in parentheses. We use the data collapsed at the race×birth-county×birth-year-month level. Cell size weights are used.

$*p < 0.10$, $**p < 0.05$, $***p < 0.01$.

Sources: GHCND weather data merged with U.S. National Vital Statistics Birth Data 2009–2018.

TABLE A7 Effects of absolute temperatures during pregnancy on birth outcomes: placebo temperatures assuming counterfactual birth date—one year prior to the actual birth year-month

	Number of births with adverse outcomes (in 1000 births)											
	Preterm birth		Very preterm birth		Extremely preterm birth		Low birthweight		Very low birthweight		NICU admission	
# Days below 10F	0.002	−0.003	0.001	0.000	0.006	0.006	−0.014	−0.017	0.014	0.016	0.024	0.031
- 1 year lag	(0.040)	(0.040)	(0.012)	(0.012)	(0.007)	(0.007)	(0.025)	(0.025)	(0.011)	(0.011)	(0.078)	(0.075)
# Days 10–20F	−0.022	−0.03	−0.01	−0.01	0.001	0.001	0.028	0.028	0.004	0.004	0.015	0.024
- 1 year lag	(0.034)	(0.034)	(0.010)	(0.010)	(0.007)	(0.007)	(0.019)	(0.019)	(0.008)	(0.008)	(0.089)	(0.090)
# Days 20–30F	−0.034	−0.036	−0.002	0.000	−0.001	−0.001	−0.01	−0.01	0.005	0.005	−0.125***	−0.122***
- 1 year lag	(0.026)	(0.027)	(0.008)	(0.008)	(0.004)	(0.004)	(0.013)	(0.013)	(0.006)	(0.006)	(0.046)	(0.046)
# Days 30–40F	−0.018	−0.022	−0.003	−0.003	−0.000	−0.000	0.000	0.001	0.002	0.002	−0.02	−0.017
- 1 year lag	(0.023)	(0.024)	(0.007)	(0.007)	(0.003)	(0.003)	(0.011)	(0.011)	(0.005)	(0.005)	(0.044)	(0.044)
# Days 40–50F	0.039*	0.037*	0.007	0.007	0.002	0.002	0.005	0.004	0.006*	0.006*	0.009	0.012
- 1 year lag	(0.022)	(0.021)	(0.005)	(0.005)	(0.003)	(0.003)	(0.010)	(0.010)	(0.003)	(0.003)	(0.040)	(0.039)
# Days 50–60F	−0.009	−0.01	−0.004	−0.004	−0.001	−0.001	−0.004	−0.006	0.000	0.000	0.02	0.019
- 1 year lag	(0.015)	(0.015)	(0.004)	(0.004)	(0.002)	(0.002)	(0.008)	(0.008)	(0.003)	(0.003)	(0.032)	(0.032)
# Days 70–80F	−0.005	−0.004	−0.004	−0.004	−0.000	−0.000	0.003	0.002	−0.002	−0.002	−0.03	−0.032
- 1 year lag	(0.016)	(0.017)	(0.003)	(0.003)	(0.002)	(0.002)	(0.007)	(0.006)	(0.002)	(0.002)	(0.029)	(0.031)
# Days 80–90F	−0.042**	−0.040*	−0.010**	−0.011**	−0.003	−0.003	−0.014	−0.013	−0.006*	−0.006*	−0.068	−0.074
- 1 year lag	(0.021)	(0.021)	(0.005)	(0.005)	(0.002)	(0.002)	(0.009)	(0.009)	(0.003)	(0.003)	(0.065)	(0.068)
# Days above 90F	−0.046	−0.044	−0.013*	−0.014*	−0.002	−0.002	−0.004	−0.004	−0.011*	−0.011**	0.012	0.008
- 1 year lag	(0.039)	(0.039)	(0.008)	(0.008)	(0.004)	(0.004)	(0.019)	(0.018)	(0.006)	(0.006)	(0.095)	(0.091)
# Days below 10F		0.059		0.033**		0.005		0.014		0.003		0.028
		(0.038)		(0.013)		(0.007)		(0.027)		(0.010)		(0.063)
# Days 10–20F		0.026		−0.007		−0.006		−0.004		−0.009		0.004
		(0.027)		(0.012)		(0.006)		(0.021)		(0.008)		(0.082)
# Days 20–30F		0.054**		0.002		0.005		0.014		0.006		−0.05
		(0.024)		(0.009)		(0.004)		(0.016)		(0.005)		(0.055)
# Days 30–40F		0.018		−0.006		−0.000		0.01		−0.006		−0.022
		(0.020)		(0.007)		(0.004)		(0.011)		(0.005)		(0.043)
# Days 40–50F		0.030*		0.005		0.001		0.018*		−0.003		0.016
		(0.017)		(0.005)		(0.003)		(0.010)		(0.004)		(0.035)
# Days 50–60F		0.02		0		0.003		0.004		0.001		0.012
		(0.014)		(0.004)		(0.003)		(0.007)		(0.003)		(0.038)

TABLE A7 (Continued)

	Number of births with adverse outcomes (in 1000 births)											
	Preterm birth		Very preterm birth		Extremely preterm birth		Low birthweight		Very low birthweight		NICU admission	
# Days 70–80F		0.018		0.002		0.003		0.008		0.002		0.006
		(0.012)		(0.004)		(0.002)		(0.007)		(0.002)		(0.022)
# Days 80–90F		0.001		0.005		0.004		0.024***		0.008**		0.041
		(0.019)		(0.005)		(0.003)		(0.009)		(0.004)		(0.046)
# Days above 90F		−0.02		0.014*		0.015***		−0.006		0.008		0.162*
		(0.033)		(0.007)		(0.004)		(0.024)		(0.006)		(0.098)
Observations	360,390	360,390	360,390	360,390	360,577	360,577	360,390	360,390	360,390	360,390	341,971	341,971
R-squared	0.495	0.495	0.345	0.345	0.281	0.281	0.514	0.514	0.325	0.325	0.288	0.288
Adj. R-squared	0.415	0.415	0.241	0.241	0.167	0.167	0.437	0.437	0.218	0.218	0.17	0.17
Mean	98.706	98.706	15.346	15.346	5.760	5.760	63.337	63.337	10.799	10.799	74.175	74.175

Notes: Each column reports regression coefficients (β_j) from Equation (1). Temperature bin 60–70F is omitted as a reference group. Robust standard errors, clustered by commuting zone, are in parentheses. We use the data collapsed at the race×birth-county×birth-year-month level. Cell size weights are used.

*p <0.10, **p < 0.05, ***p < 0.01.

Sources: GHCND weather data merged with U.S. National Vital Statistics Birth Data 2009–2018.

TABLE A8 Effects of absolute temperatures during pregnancy on birth outcomes: placebo temperatures assuming counterfactual birth date—one year after the actual birth year-month

	Number of births with adverse outcomes (in 1000 births)											
	Preterm birth		Very preterm birth		Extremely preterm birth		Low birthweight		Very low birthweight		NICU admission	
# Days below 10F	0.046	0.039	0.012	0.01	−0.004	−0.005	−0.011	−0.012	−0.014	−0.014	0.06	0.053
- 1 year lead	(0.042)	(0.044)	(0.013)	(0.014)	(0.007)	(0.007)	(0.023)	(0.023)	(0.010)	(0.010)	(0.092)	(0.095)
# Days 10–20F	0.009	0.004	−0.004	−0.004	−0.005	−0.005	0.009	0.006	0.005	0.004	0.049	0.055
- 1 year lead	(0.033)	(0.033)	(0.011)	(0.011)	(0.006)	(0.006)	(0.025)	(0.025)	(0.009)	(0.009)	(0.067)	(0.067)
# Days 20–30F	0.025	0.022	−0.004	−0.003	−0.005	−0.004	0.000	0.001	−0.008	−0.007	−0.033	−0.026
- 1 year lead	(0.023)	(0.024)	(0.007)	(0.007)	(0.004)	(0.004)	(0.014)	(0.014)	(0.005)	(0.005)	(0.049)	(0.053)
# Days 30–40F	0.034	0.026	0.000	−0.001	−0.002	−0.002	0.006	0.005	−0.004	−0.005	0.080*	0.087*
- 1 year lead	(0.025)	(0.025)	(0.007)	(0.007)	(0.004)	(0.004)	(0.011)	(0.012)	(0.005)	(0.005)	(0.048)	(0.050)
# Days 40–50F	−0.011	−0.016	−0.003	−0.004	−0.003	−0.003	−0.005	−0.006	−0.003	−0.003	−0.008	−0.005
- 1 year lead	(0.024)	(0.025)	(0.005)	(0.005)	(0.003)	(0.003)	(0.009)	(0.010)	(0.003)	(0.003)	(0.036)	(0.035)
# Days 50–60F	0.008	0.005	0.001	0.001	−0.000	−0.000	0.009	0.008	−0.001	−0.001	0.018	0.023
- 1 year lead	(0.018)	(0.018)	(0.004)	(0.004)	(0.002)	(0.002)	(0.007)	(0.007)	(0.003)	(0.003)	(0.033)	(0.032)
# Days 70–80F	0.009	0.012	0.000	0.000	0.001	0.002	−0.004	−0.003	−0.002	−0.001	0.031	0.032
- 1 year lead	(0.013)	(0.012)	(0.004)	(0.004)	(0.002)	(0.002)	(0.007)	(0.008)	(0.002)	(0.002)	(0.024)	(0.025)
# Days 80–90F	−0.003	−0.002	0.002	0.002	−0.000	0.000	−0.008	−0.006	−0.001	0	−0.005	−0.004
- 1 year lead	(0.018)	(0.019)	(0.005)	(0.005)	(0.002)	(0.003)	(0.009)	(0.009)	(0.004)	(0.004)	(0.034)	(0.034)
# Days above 90F	−0.05	−0.048	0.01	0.01	0.002	0.002	0.005	0.005	0.011	0.012	−0.113	−0.114
- 1 year lead	(0.038)	(0.037)	(0.008)	(0.008)	(0.005)	(0.005)	(0.024)	(0.024)	(0.008)	(0.008)	(0.128)	(0.124)

(Continues)

TABLE A8 (Continued)

	Number of births with adverse outcomes (in 1000 births)											
	Preterm birth		Very preterm birth		Extremely preterm birth		Low birthweight		Very low birthweight		NICU admission	
# Days below 10F		0.053		0.031**		0.007		0.014		0.006		0.027
		(0.039)		(0.013)		(0.007)		(0.026)		(0.009)		(0.063)
# Days 10–20F		0.022		−0.006		−0.005		−0.009		−0.007		0.001
		(0.028)		(0.012)		(0.006)		(0.020)		(0.008)		(0.082)
# Days 20–30F		0.048*		0.000		0.005		0.012		0.006		−0.066
		(0.024)		(0.009)		(0.004)		(0.016)		(0.005)		(0.055)
# Days 30–40F		0.017		−0.006		0.001		0.008		−0.004		−0.022
		(0.020)		(0.007)		(0.004)		(0.011)		(0.005)		(0.042)
# Days 40–50F		0.022		0.003		0.000		0.017*		−0.002		0.004
		(0.017)		(0.005)		(0.003)		(0.010)		(0.003)		(0.034)
# Days 50–60F		0.015		0.000		0.003		0.005		0.002		0.005
		(0.014)		(0.004)		(0.003)		(0.006)		(0.003)		(0.038)
# Days 70–80F		0.026**		0.003		0.003*		0.009		0.002		0.015
		(0.013)		(0.004)		(0.002)		(0.007)		(0.003)		(0.021)
# Days 80–90F		0.012		0.006		0.004		0.024**		0.007*		0.05
		(0.018)		(0.005)		(0.003)		(0.009)		(0.004)		(0.049)
# Days above 90F		−0.017		0.013*		0.014***		−0.007		0.006		0.155*
		(0.033)		(0.007)		(0.004)		(0.024)		(0.006)		(0.090)
Observations	359,285	359,285	359,285	359,285	359,474	359,474	359,285	359,285	359,285	359,285	340,818	340,818
R-squared	0.495	0.495	0.345	0.345	0.281	0.281	0.514	0.514	0.325	0.325	0.288	0.288
Adj. R-squared	0.416	0.416	0.242	0.242	0.167	0.167	0.438	0.438	0.219	0.219	0.171	0.171
Mean	98.706	98.706	15.346	15.346	5.760	5.760	63.337	63.337	10.799	10.799	74.175	74.175

Notes: Each column reports regression coefficients (β_j) from Equation (1). Temperature bin 60–70F is omitted as a reference group. Robust standard errors, clustered by commuting zone, are in parentheses. We use the data collapsed at the race×birth-county×birth-year-month level. Cell size weights are used.

*$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

Sources: GHCND weather data merged with U.S. National Vital Statistics Birth Data 2009–2018.

TABLE A9 Effects of temperatures above high cutoff or below low cutoff during pregnancy on birth outcomes

	Number of births with adverse outcomes (in 1000 births)							
	Preterm birth	Very preterm birth	Extremely preterm birth	Low birthweight	Very low birthweight	NICU admission	# Required assisted ventilation	Gestational hypertension
# Days above hot cutoff	0.074*	0.024*	0.003	0.032	0.012	−0.026	0.173	0.108**
	(0.044)	(0.014)	(0.008)	(0.027)	(0.010)	(0.115)	(0.170)	(0.043)
# Days below cold cutoff	0.065*	0.023*	0.012	0.029	0.003	0.033	0.182**	−0.035
	(0.033)	(0.013)	(0.008)	(0.024)	(0.009)	(0.065)	(0.092)	(0.035)
Observations	366,265	366,265	366,265	366,265	366,265	347,441	347,441	366,231
R-squared	0.492	0.342	0.278	0.511	0.323	0.287	0.342	0.461
Adj. R-squared	0.412	0.240	0.166	0.435	0.217	0.170	0.235	0.376
Mean	98.706	15.346	5.760	63.337	10.799	74.175	34.75	50.35

Notes: Temperature bin between low and high cutoff is omitted as a reference group. Hot cutoff is the temperature threshold where the county experiences less than 10 days in a given year. Cold cutoff is vice versa. For more detail, refer to IV. B. Robustness check section. Robust standard errors, clustered by commuting zone, are in parentheses. We use the data collapsed at the race×birth-county×birth-year-month level. Cell size weights are used.

*$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

Sources: GHCND weather data merged with U.S. National Vital Statistics Birth Data 2009–2018.

TABLE A10 Effects of temperatures above high cutoff or below low cutoff during pregnancy on birth outcomes: By race of the mother

		Number of births with adverse outcomes (in 1000 births)							
		Preterm birth	Very preterm birth	Extremely preterm birth	Low birthweight	Very low birthweight	NICU admission	# Required assisted ventilation	Gestational hypertension
# Days below cold cutoff	Non-hispanic white	0.047	0.027**	0.009	−0.001	0.006	0.094	0.140	−0.051
		(0.037)	(0.013)	(0.007)	(0.025)	(0.010)	(0.105)	(0.088)	(0.039)
	Non-hispanic black	0.156	0.029	0.015	0.136	0.008	0.030	0.402**	−0.043
		(0.105)	(0.047)	(0.031)	(0.090)	(0.039)	(0.153)	(0.173)	(0.093)
	Hispanic	0.016	0.021	−0.003	−0.002	0.010	−0.089	0.136	−0.030
		(0.076)	(0.030)	(0.020)	(0.045)	(0.020)	(0.108)	(0.176)	(0.065)
	Other	0.206**	−0.006	−0.040**	0.131	−0.045**	0.139	0.238*	0.062
		(0.101)	(0.027)	(0.017)	(0.083)	(0.022)	(0.189)	(0.138)	(0.068)
# Days above hot cutoff	Non-hispanic white	0.002	0.021	0.024***	−0.018	0.009	−0.097	−0.043	0.056
		(0.041)	(0.015)	(0.008)	(0.029)	(0.012)	(0.116)	(0.158)	(0.044)
	Non-hispanic black	0.181	0.037	−0.018	0.045	−0.015	−0.125	0.174	0.152
		(0.149)	(0.056)	(0.032)	(0.091)	(0.035)	(0.306)	(0.259)	(0.109)
	Hispanic	0.121	0.019	−0.001	0.068	0.027	0.221	0.611*	0.164**
		(0.092)	(0.033)	(0.018)	(0.055)	(0.022)	(0.287)	(0.312)	(0.074)
	Other	0.199	0.008	0.009	0.281***	0.014	−0.139	0.136	0.089
		(0.123)	(0.041)	(0.030)	(0.099)	(0.031)	(0.331)	(0.200)	(0.063)
N	Non-hispanic white	205,260	205,260	205,260	205,260	205,260	194,962	194,962	205,235
	Non-hispanic black	59,882	59,882	59,882	59,882	59,882	55,571	55,571	59,873
	Hispanic	67,181	67,181	67,181	67,181	67,181	64,413	64,413	67,181
	Other	33,942	33,942	33,942	33,942	33,942	32,495	32,495	33,942
Mean	Non-hispanic white	84.863	11.65	3.909	51.704	7.859	68.803	37.718	53.839
	Non-hispanic black	148.314	31.658	14.034	112.945	24.246	100.706	41.547	62.342
	Hispanic	103.351	14.864	5.415	58.928	9.949	71.961	26.545	39.921
	Other	87.534	11.730	4.081	65.984	8.545	69.249	25.226	32.188

Notes: Temperature bin between low and high cutoff is omitted as a reference group. Hot cutoff is the temperature threshold where the county experiences less than 10 days in a given year. Cold cutoff is vice versa. For more detail, refer to IV. B. Robustness check section. Robust standard errors, clustered by commuting zone, are in parentheses. We use the data collapsed at the race×birth-county×birth-year-month level. Cell size weights are used.

*$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

Source: GHCND weather data merged with U.S. National Vital Statistics Birth Data 2009–2018.

TABLE A11 Effects of absolute temperatures during pregnancy on birth outcomes: Controlling for air quality index

	Controlling for AQI						Without AQI controls (using same AQI samples)					
	Preterm birth	Very preterm birth	Extremely preterm birth	Low birthweight	Very low birthweight	NICU admission	Preterm birth	Very preterm birth	Extremely preterm birth	Low birthweight	Very low birthweight	NICU admission
# Days below 10F	0.113**	0.045***	0.018**	0.063**	0.021*	0.094	0.115**	0.044***	0.018*	0.063**	0.020*	0.090
	(0.047)	(0.016)	(0.009)	(0.031)	(0.012)	(0.083)	(0.047)	(0.016)	(0.009)	(0.031)	(0.012)	(0.083)
# Days 10–20F	0.006	−0.014	−0.011	−0.030	−0.016*	0.003	0.003	−0.015	−0.011	−0.030	−0.016*	0.001
	(0.032)	(0.015)	(0.007)	(0.025)	(0.009)	(0.098)	(0.032)	(0.015)	(0.007)	(0.025)	(0.009)	(0.098)
# Days 20–30F	0.075***	0.003	0.007	0.012	0.009	−0.079	0.072***	0.003	0.007	0.012	0.009	−0.083
	(0.026)	(0.010)	(0.005)	(0.018)	(0.006)	(0.064)	(0.026)	(0.010)	(0.005)	(0.018)	(0.006)	(0.063)
# Days 30–40F	0.013	−0.007	−0.000	0.013	−0.006	−0.027	0.011	−0.008	−0.001	0.012	−0.006	−0.032
	(0.021)	(0.008)	(0.004)	(0.012)	(0.005)	(0.050)	(0.021)	(0.008)	(0.004)	(0.012)	(0.005)	(0.050)
# Days 40–50F	0.027	0.001	0.000	0.016	−0.002	0.016	0.025	0.000	0.000	0.015	−0.002	0.012
	(0.019)	(0.005)	(0.003)	(0.011)	(0.004)	(0.043)	(0.019)	(0.005)	(0.003)	(0.011)	(0.004)	(0.041)
# Days 50–60F	0.017	−0.001	0.004*	0.003	0.003	0.005	0.015	−0.001	0.004*	0.003	0.002	0.003
	(0.016)	(0.005)	(0.003)	(0.007)	(0.003)	(0.047)	(0.016)	(0.005)	(0.003)	(0.007)	(0.003)	(0.046)
# Days 70–80F	0.017	0.002	0.004**	0.006	0.002	0.009	0.024*	0.003	0.004**	0.006	0.002	0.013
	(0.013)	(0.004)	(0.002)	(0.007)	(0.003)	(0.023)	(0.014)	(0.004)	(0.002)	(0.007)	(0.003)	(0.024)
# Days 80–90F	−0.004	0.008	0.006**	0.023**	0.010**	0.058	0.004	0.009*	0.006**	0.023**	0.010**	0.056
	(0.020)	(0.005)	(0.003)	(0.010)	(0.004)	(0.063)	(0.020)	(0.005)	(0.003)	(0.010)	(0.004)	(0.058)
# Days above 90F	−0.042	0.014	0.015***	−0.015	0.009	0.149	−0.020	0.016**	0.016***	−0.014	0.009	0.168
	(0.037)	(0.008)	(0.005)	(0.025)	(0.006)	(0.096)	(0.036)	(0.008)	(0.005)	(0.025)	(0.006)	(0.103)
Observations	197,310	197,310	197,313	197,310	197,310	188,902	197,310	197,310	197,313	197,310	197,310	188,902
R-squared	0.582	0.418	0.337	0.605	0.396	0.301	0.581	0.418	0.337	0.605	0.396	0.301
Adj. R-squared	0.516	0.328	0.233	0.544	0.303	0.189	0.516	0.328	0.233	0.544	0.303	0.189
Mean	98.706	15.346	5.760	63.337	10.799	74.175	98.354	15.324	5.831	63.297	10.877	75.837

Notes: Each column reports regression coefficients (β_j) from Equation (1). Temperature bin 60–70°F is omitted as a reference group. Robust standard errors, clustered by commuting zone, are in parentheses. We use the data collapsed at the race×birth-county×birth-year-month level. Cell size weights are used.

*$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

Source: GHCND weather data merged with U.S. National Vital Statistics Birth Data 2009–2018. Air Quality Index data from Environmental Protection Agency (EPA).