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The Impact of Extreme Temperatures on Newborn Health in California

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SUMMARY:

This paper provides new evidence on the impact of prenatal temperature exposure on health at birth. We combine hospital data on 11 million observations in California between 1991 and 2011 with ZIP code and trimester-specific measures of in utero temperature exposure. Using a spatial fixed effects model, we find that warm-to-hot days have substantial adverse effects on birth weight, gestational age and fetal death in the second and third trimesters of pregnancy. Separating births by season of conception, we find that the negative impact of extreme heat is not confined to the second and third trimesters so much as to the cool seasons: irrespective of the coinciding trimester, winter-time thermal exposure inhibits fetal development; it also delivers greater stress to the fetus the later it occurs in pregnancy. Our results are robust to controlling for various forms of air pollution and precipitation.
Keywords: extreme temperature, birth weight, gestation, fetal death, ZIP code.

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1. Introduction

As the planet warms, there is a growing imperative to understand the human health implications of our changing climate. One of the high-confidence estimates in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) is an overall increase (decrease) in the number of warm (cold) days and nights across North America since about 1950 (Hartmann, D.L. et al. 2013, p. 211). Although the report spells out how this shift in the temperature distribution will compromise human health, it does not contain estimates specifically for the health of newborns (IPCC 2014, p. 69). Indeed, newborn health is a relatively nascent focus in the climate-health literature.[1] In contrast, there have been a significant number of studies that have evaluated the impact of temperature on adult health as well as on outcomes indirectly related to human health. In the latter subset, studies have found that extreme temperatures damage crop yields (Schlenker and Roberts 2009), reduce hours worked in industries with high exposure to extreme heat (Graff-Zivin and Neidell 2014), decrease income per capita (Deryugina and Hsiang 2014), and increase the risk of conflict and civil war (Carleton, Hsiang and Burke 2016). Similarly, though still fewer in number, several studies show the deleterious effects of extreme temperatures on adult health outcomes, including suicide rates (Burke et al. 2018; Carleton 2017), elderly mortality (Deschenes and Moretti 2009), and emergency department visits and hospitalizations (White 2017).[2] Since a large body of research identifies in utero development as a critical period with long-arm consequences late into the life course,[3] we seek to provide a systematic assessment of the relationship of prenatal temperature exposure to newborn health.

A combination of anthropological and obstetrical research can be adduced to support the claim that ambient temperatures are related to health at birth. Sleep is one possible pathway: Okamoto-Mizuno and Mizuno (2012) show that both heat and cold exposure disrupt human sleep and Okun et al. (2009) show that disturbed sleep in the first trimester is a risk factor for adverse birth outcomes. Physiological changes in pregnancy, such as weight gain, higher fat deposition and more rapid metabolism, tend to diminish natural cooling responses to high temperatures; this increases the risk of maternal heat stress, which, as Wells and Cole (2002) show, is associated with low birth weight. Konkel (2019) points out that pregnant women are also more susceptible to dehydration, which can trigger early labor. She also cites animal studies on how heat exposure in pregnancy disrupts normal protein synthesis, brings on

[1] See Dell, Jones and Olken (2014) for a review of the economic literature on the impacts of climate and weather shocks. They cite only five studies (p.763) in the context of infant health, two of which focus on the United States.
[2] See Carleton and Hsiang (2016) for an overview of the social and economic impacts of climate.
[3] Almond and Currie (2011) and more recently, Almond, Currie and Duque (2018) provide a comprehensive review of what has come to be known as the fetal origins literature, which documents evidence of how prenatal events and exposures have lifelong consequences.

inflammation and oxidative stress, all of which could slow fetal development and culminate in low birth weight. So while the etiologies of low birth weight are varied, they tend to make thermoregulation less efficient and disrupt foetal nutrition (Konkel 2019; Bouchama and Knochel 2002).

Our empirical analysis draws on a large dataset with detailed information on the outcomes of individual pregnancies over time so that variations in exposure to extreme temperature can be registered and their impacts on newborn health assessed. This dataset, from the California Department of Public Health (CDPH), contains birth weight, gestational age and fetal death information on over 10 million hospital observations in California from 1991 to 2011, including the mother's residence ZIP code during pregnancy and other relevant demographic characteristics. We combine this dataset with precise measurements of ambient temperature exposure for each observation based on the ZIP codes in which the pregnant mothers resided. This data structure allows us to implement a spatial fixed effects analysis that helps identify whether extreme temperatures are plausibly causally related to health at birth, and how this relationship behaves in each trimester of pregnancy. Since daily mean temperatures in California encompass a wide range of values from about 40°F to over 90°F, we represent in utero exposure with seven 10°F-wide bins in this range. Further, since California's climate normals place its average annual temperature between 55°F and 60°F, we reserve extreme heat for daily mean temperatures of 80°F or more.

Our analysis makes four contributions. First, we evaluate the impact of in utero thermal stress on birth weight as well as on gestational age. As Strand, Barnett and Tong (2011) find in their review of the literature on the influence of ambient temperature on birth outcomes, studies consider either low birth weight or preterm birth as their outcome of interest. For example, Deschenes, Greenstone and Guryan (2009) – whom we follow methodologically – use a sample of 37 million singleton births between 1972 and 1988 from the coterminous United States and the District of Columbia to determine if extreme temperatures during pregnancy reduce birth weight. However, they do not report thermal impacts on gestational age. Barreca and Schaller (2019), who use a sample of 56 million births in the United States between 1969 and 1988, estimate only the aggregate gestational loss due to heat exposure (about 25,000 annual preterm births). Often, studies on temperature and birth weight tend to restrict the sample to singleton births delivered at or near full-term, implicitly discarding gestational age as an outcome of interest. Our work corrects for this anomaly. We explicitly analyze how prenatal thermal exposure determines gestational age as well as birth weight in each trimester. The analysis by trimester recognizes that the temperature impact is likely to vary by the stage of gestation; indeed, we find that with regard to birth weight, extreme heat is not harmful in the first trimester, unambiguously harmful in the second trimester and somewhat harmful in the third trimester. Similarly, extreme heat is not harmful to gestation until the third trimester.

Second, we investigate how extreme temperatures affect fetal mortality. Again, we find that only second and third trimester heat increase fetal death. Reading these results together with the results for birth weight, we see that whenever heat depresses birth weight, the estimated impact on fetal death is negative and statistically significant. If extreme heat culls fetuses that might be born with very low birth weight, the surviving sample is positively selected, which implies that we underestimate the true impact of heat on birth weight.

Third, we examine how the impact of extreme temperatures on health at birth depends on the season of conception. We find that for any given season of conception, the impact of extreme heat on birth weight is negative in the trimesters that overlap or follow wintertime, and positive in the trimesters that overlap or follow summertime. The size of these impacts is greater in later trimesters; thus, winter-time thermal stress in the third trimester hits birth weight harder than it does in the second or first trimester. By pinpointing the confluence of season and trimester, we refine our understanding of when heat inhibits or promotes fetal development. A recurring concern with seasonality in births, prompted by Buckles and Hungerman (2013), is that it reflects seasonal patterns in the maternal determinants of newborn health, rather than differences in prenatal temperature exposure. Through a series of tests, we confirm that our temperature impacts on birth weight are not confounded by the timing of conception.

Fourth, and from a measurement perspective, we add to the above literature by measuring thermal exposure at the ZIP code of each birth observation rather than the county of residence. This granularity is particularly important in California where counties are much larger in area relative to counties in most other states and encompass various geographies. In the Appendix, we show how county-level temperature data is a poor approximation of various ZIP-code-level temperature distributions. When we subsequently regress health at birth on prenatal exposure, we use ZIP code fixed effects to erase stable confounders, be they observed or unobserved. We assume that this renders the remaining variation in ZIP code temperature exposure random, and that a causal relationship can be deciphered by comparing how average health at birth in a ZIP code changes when only temperature changes.

Finally, by using a relatively recent dataset—1991 through 2011, a period in which mean temperatures had already risen by 0.9°F relative to 1960–1979 (Schleussner et al. 2017) – our estimates are likely to capture future impacts of warming on newborns more accurately relative to earlier analysis.

Overall, our results corroborate previous studies, such as Deschenes, Greenstone and Guryan (2009), Basu et al. (2018), Basu, Sarovar and Malig (2016), Basu, Malig and Ostro (2010) and Andalón et al. (2016), in finding that extreme heat exacts a toll on newborn health mainly in the second and third trimesters of pregnancy. Briefly exploring the mechanisms behind our results, we find little support for economic drivers, which leads us to conclude that biological responses during pregnancy produce the thermal impacts on newborn health.

2. Data

2.1. Sample Selection

The California Office of Statewide Health Planning and Development (OSHPD) houses a comprehensive database on all hospitalizations within the state of California. The OSHPD provides a research database called Linked Birth Files to study birth and delivery outcomes, beginning with the 1991 calendar year reporting period. The most recent year for which such data is available is 2011. For several reasons, this database is ideal for our research: it specifies the mother's ZIP code of residence during pregnancy, it covers a long period of time, and it provides information about the parents of newborns.[4] The granular location data combined with information on gestation enables us to develop precise measures of prenatal exposure to extreme temperatures. The accompanying parent data helps us control for parental characteristics that could modify the effect of extreme temperatures on newborn health.

Joining data on newborns and parents for the years, 1991-2011, we obtain 11,633,863 observations. We focus on births with a gestational age of at least 26 completed weeks, i.e. two full trimesters, and so drop 44,863 observations (0.4% of sample). We also drop 835 observations where the recorded birth weight exceeds 6000 grams. We then exclude observations missing information on one or more of the following variables: the mother's location (i.e. her residential ZIP code), the infant's date of birth, the length of gestation and birth weight; these adjustments reduce the sample to 10,973,357 observations, which is 95% of the initial extract. Finally, we restrict the sample to mothers in the ages of 13 through 49, and fathers over thirteen years of age.[5] This puts the analysis sample at 10,970,246 unique observations.

[4] The OSHPD provides confidential patient-level data sets to researchers eligible through the Information Practices Act (CA Civil Code Section 1798 et seq.) for study purposes. Because location variables are potentially identifying information, particularly in conjunction with date of birth data, the OSHPD anonymizes record identifiers and binds end-users to confidentiality and non-sharing agreements as a condition of access to its database.

[5] This is consistent with both the literature (cf. Deschenes et al. 2009; Barreca and Schaller 2019) and the Centers for Disease Control and Prevention (CDC), which typically presents birth and fertility rates with reference to the reproductive age-group of 15-44 (see for instance, Martin et al. 2018; 2019).

2.2. Variables

We select three measures of newborn health to investigate the in utero impact of extreme temperatures: birth weight (reported in grams), gestation length (reported in days) and fetal death (reported as a binary outcome). Fetal death refers to the intrauterine death of a fetus at any gestational age. It does not include induced terminations of pregnancy. In California, fetal deaths are required to be reported when the fetus has advanced to or beyond the twentieth week of gestation (Kowaleski 1997). The OSHPD's data on fetal deaths includes characteristics of the fetus, such as sex, birthweight, weeks of gestation as well as data on the mother's health and demographic characteristics. The gestation length is calculated as the interval between the mother's reported date of her last normal menstrual period and the infant's date of birth. If only the month and year of menses were reported, the OSHPD assumes the date to be the fifteenth of the month. To avoid confounding the impact of extreme temperatures with the array of factors that typically affect newborn health, we utilize the parent dataset to construct control variables. The parent dataset includes information on the father's age and education level as well as a large number of maternal covariates such as the month she commenced seeking prenatal care, her age, race, health insurance coverage, educational attainment and ZIP code of residence.

Our main explanatory variable is the newborn's in utero exposure to temperature. The National Oceanic and Atmospheric Administration (NOAA) provides daily climate summaries in a product called the Global Historical Climatology Network Daily (GHCN-Daily), collating records from over 100,000 land-surface stations across the globe, including some 820 in California. We extract daily minimum and maximum temperature data from 1990 till 2012 for California from the GHCN-Daily. For the remaining stations[6], we compute station-level daily mean temperatures as a simple average of the daily maximum and minimum data. In the next section, we describe how we build infant-specific in utero exposures to extreme temperature from these station-level daily mean data.

2.3. In Utero Exposure

To summarize the weather histories associated with each of the nearly 11 million observations in our dataset, we begin by constructing the daily mean temperature histories of the ZIP code tabulation areas (ZCTAs).[7] First, we find the nearest three station neighbors to each of the 1764

[6] About 390 to 650, depending on the year. See notes by Figure 1. In a robustness check (Appendix Table A2, panel C), we held the set of stations constant – i.e. we computed in utero thermal exposure using data only from the 413 stations operating in 1991 – and found no change in the estimated temperature impacts on birth weight.
[7] Unlike a county or census tract, ZIP codes do not have a standard geographic representation; ZIP codes were devised by the US Postal Service in 1963 to link various street addresses for efficient mail delivery. However, the US Census Bureau provides a geographic approximation called a ZIP code tabulation area that coincides, for most residences, with the 5-digit ZIP code.

ZCTAs in the state. Next, we assign the ZCTA its nearest station's daily mean temperature data, filling gaps in the record with data from the next nearest station with a non-missing value.[8] This process gives us a near-complete assessment of ZIP code-level temperature histories over the sample period; in any given year, fewer than 0.5% of ZIP code days are missing temperature data. We constructed other measures to summarize ZCTA temperature histories, such as an inverse-distance weighted average of station-level temperatures using stations within twenty miles of ZCTA centroids, but this did not yield a smaller rate of missing values. In any given year, for 80-90% of ZCTAs, the nearest three stations can be found within 15 miles of the centroids. While the nearest station is typically within 10 miles of the centroid, the second-nearest is at just over 10 miles. As a result, we capture temperature data at the ZIP code level with much higher precision than previous studies that have constructed county-level temperatures.[9]

Our process of assigning weather stations to ZCTAs leaves us vulnerable to spatial correlation in ZIP code temperatures. By allowing individual stations to be linked to any number of ZCTAs as their nearest neighbor, we might inadvertently limit spatial variation in temperatures and induce measurement error in prenatal exposures. In the Appendix, we evaluate the threat of spatial correlation and show the robustness of our results.[10]

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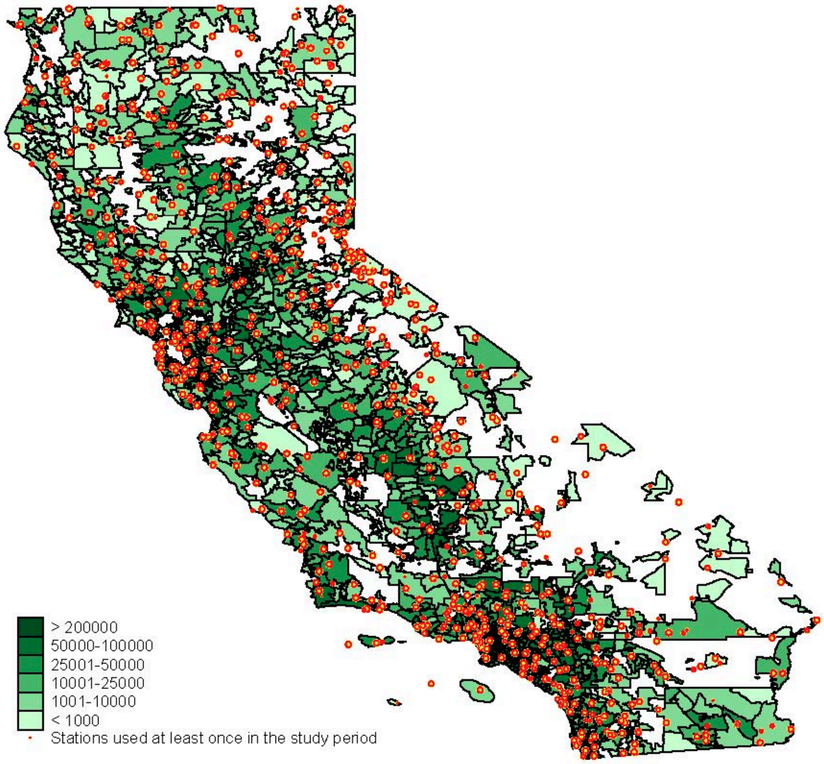
[8] For any given ZCTA and year, the pair-wise correlations between the daily mean temperatures at the nearest three stations ranges between 0.81 and 0.97. This high degree of positive correlation is why we choose not to draw upon the temperature data of the second- and third-nearest stations except to fill in blanks in the nearest station's data. As a result, over 91% of the ZCTA-level daily temperature data comes from the nearest station. For more information, please see Appendix Table A1.

[9] For instance, both Deschenes et al. (2009) and Deschenes and Greenstone (2011) filter stations using a 200-kilometre (i.e. 124-mile) radius of county centroids. Barreca and Schaller (2019) apply a 100-mile radius whereas Barreca (2012) selects stations within a 50-mile radius of county centroids to construct county-month weather data.

[10] We run a simple visual check for spatial dependence using a contiguity weights matrix (Appendix Figure A1) and find that average temperatures in contiguous ZCTAs are indeed more alike than the average temperatures in non-adjacent ZCTAs. A Moran test for spatial dependence based on the contiguity weighting matrix rejected the null of no spatial autocorrelation (the p-value for the calculated χ^2 was effectively zero). To the extent that spatial correlation in temperatures is a consequence of several ZCTAs sharing the same weather station, we could potentially reduce that correlation by capping the number of ZCTA matches per station-year. In Appendix Figure A2, we see that the greatest number of ZCTAs matched to a single station as their nearest neighbor is 41, while the median number of matches is 3 and the mean is 8. So, we restrict the number of ZCTA matches to no more than twenty per station-year. Isolating and dropping instances where a station was linked to more than 20 ZCTAs in a year, we remove about a fifth of the sample. We then re-estimate the birth weight regression and report on the sensitivity of our results in panel B of Appendix Table A2. The estimated thermal impacts on birth weight are slightly larger for the third trimester in the extreme heat bins when spatial dependence has been reduced, a result which is also consistent with a reduction in measurement error.

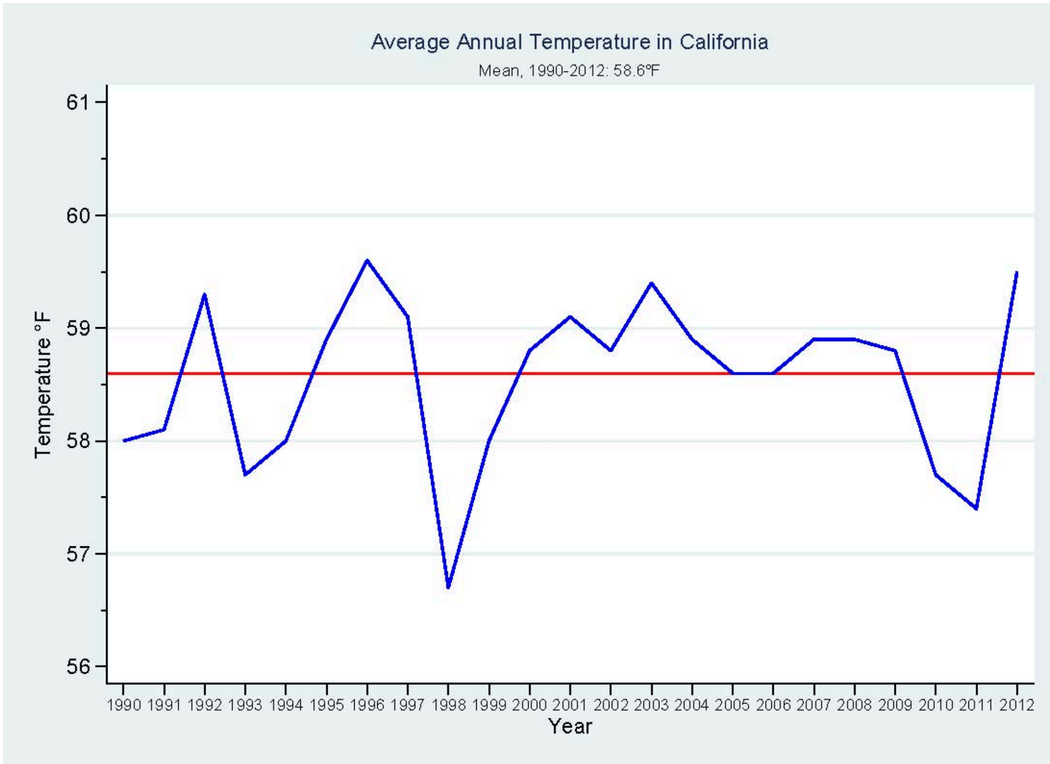
FIGURE 1. WEATHER STATIONS AND ZIP CODE TABULATION AREAS IN CALIFORNIA



		ZCTAs per station		
Year	**Stations**	**Mean**	**Min**	**Max**
1990	395	10.9	1	41
1991	413	11.2	1	41
1992	439	10.7	1	41
1993	447	10.5	1	41
1994	455	10.6	1	41
1995	469	10.3	1	41
1996	489	10.2	1	41
1997	503	9.9	1	41
1998	532	8.8	1	40
1999	566	7.9	1	36
2000	592	7.9	1	34
2001	628	7.6	1	34
2002	660	7.5	1	35
2003	673	7.3	1	34
2004	687	7.2	1	34
2005	679	7.2	1	34
2006	665	7.6	1	38
2007	662	7.6	1	38
2008	653	7.7	1	38
2009	663	7.6	1	38
2010	656	7.5	1	34
2011	652	8	1	40
2012	653	7.7	1	38

Note: Weather stations used in the study are overlaid on a choropleth map of ZIP code tabulation areas (ZCTA). The ZCTAs are shaded relative to their 2010 Census population counts. The accompanying table shows the number of weather stations available to be matched to ZCTAs for each year in the study as well as the mean, minimum and maximum number of ZCTAs matched to stations in a given year. The rise in the number of active stations reflects the growth in NOAA's Cooperative Observer Program, the citizen volunteer-run climatological observation network dating back to 1890.

FIGURE 2. AVERAGE ANNUAL TEMPERATURE IN CALIFORNIA, 1990–2012



Note: Temperature data comes from the NOAA National Centers for Environmental information, Climate at a Glance: Statewide Time Series, published February 2020, retrieved on February 14, 2020, from https://www.ncdc.noaa.gov/cag/.

To move from ZIP code-level histories to in utero exposure, consider Figure 2, which shows a long-term upward trend in California's average annual temperature. This trend translates into daily experience as an increase in the number of hot days per year, or more generally, an increase in extreme temperature events. Therefore, in utero exposure to extreme temperatures can be cast as the number of hot (and cold) days experienced by the fetus over the gestation period at the mother's location. Unlike most studies in the US climate-health literature, we fix location in terms of ZIP code, rather than county. This is largely because the average California county is nearly three times the size of the average county in the United States by area (2686 sq. miles compared to 998 sq. miles) and geography induces significant differences in mean temperature within counties.[11]

[11] To punctuate this point, six counties in California are larger in land area than the state of Connecticut (5,567 mi^2), with one county, San Bernardino (20,057 mi^2), over 3.5 times so. In Appendix Figure A3, we show how emphasizing the county temperature distribution over ZIP code distributions would collapse substantial variability and differences in extreme temperature events observed at different ZIP codes within the same county.

For the state of California, we set the threshold for extreme heat at a daily mean temperature of 90°F, and for extreme cold at 40°F, and group the intervening temperatures in bins of width 10°F each.[12] In all, seven bins capture the range of daily mean temperatures in our sample: below 40°F, 40-50°F, 50-60°F, 60-70°F, 70-80°F, 80-90°F and above 90°F. In utero exposure to (extreme) temperatures over a given period of time and at a given location is simply the number of days observed in these seven bins in each trimester.

°F	32.0	40.0	50.0	60.0	70.0	80.0	90.0	100.0
°C	0.0	4.4	10.0	15.6	21.1	26.7	32.2	37.8

We use the mother's reported date of her last menstrual period to demarcate the trimesters. Then, using the daily mean temperature data at the mother's residence ZIP code, we characterize in utero exposure over a trimester by dividing the 91 days in each trimester among the seven bins. In so doing, we assume every infant was exposed to three complete trimesters of gestation, regardless of their gestational age. This confers empirical ease to studying the cumulative effects of temperature on birth weight, our main outcome of interest. Even so, we establish that our results do not hinge on a particular choice of third trimester length. Since 97% of our sample sees a third trimester of at least 60 days, we estimate thermal impacts on birth weight assuming every infant had a third trimester of exactly 60 days. We find that missing some real third trimester exposure for some births, rather than attributing exposure that did not occur to some other births, does not change our results in any appreciable way.[13] As the next section shows, our preferred estimation is the birth weight temperature equation that does not control for gestation because gestation is endogenous to, and a determinant of birth weight.

Seasonality in In Utero Exposure

The timing of conception introduces a seasonal dimension to in utero exposure. Consider how the month of conception determines which trimester, if any, will coincide with peak summer (historically, the months of July, August and September in California). Suppose all births occur after a full term, i.e. a 273-day gestation period. It is straightforward to see that a baby conceived in

- Dec/Jan/Feb undergoes the hottest possible third trimester
- Mar/Apr/May undergoes the hottest possible second trimester
- June/July/Aug undergoes the hottest possible first trimester

[12] Alternative thresholds for extreme heat and extreme cold, such as 100°F and 30°F or 85°F and 45°F respectively, were evaluated with no appreciable impact on our baseline results.
[13] See Appendix Table A3.

- September/October/November faces no exposure to peak summer during gestation

We split our full sample of nearly 11 million births into four sub-samples along the above lines to investigate how the timing of conception alters the temperature gradient in birth weight. In section 4, we examine how in utero exposure to peak summer heat in different trimesters affects birth weight. We also examine how escaping such exposure throughout gestation simply due to the timing of conception affects birth weight.

2.4. Descriptive Statistics

Tables 1A and 1B report descriptive statistics for the analysis sample. Table 1A summarizes in utero exposure, first for the full sample, and then in the coldest and hottest years in the sample period. Figure 3, which visualizes the summary statistics for the full sample, shows that the prenatal thermal exposure of the average newborn is very similar across the three trimesters. For example, in every trimester, the average newborn was exposed to approximately five days with mean temperature in the range of 80-90°F and about 8 days in the mean temperature range of 40-50°F. In 1998, the coldest sample year, average exposure to cool temperatures exceeds the full sample average only in the first trimester while average exposure to warm temperatures exceeds the full sample average in the second and third trimesters. In 1996, the hottest sample year, average exposure is distinctly skewed towards warmer than cooler temperatures in all trimesters, when compared with the full sample.

Table 1B presents summary statistics on the newborns and parents. The mean birth weight is 3331 grams with a standard deviation of 590 grams.[14] The mean length of gestation is 274 days with a standard deviation of 16. There were approximately three fetal deaths per 1000 live births. Ninety-seven percent of births resulted in singleton babies; 49% of births were female, and 47% were recorded as Hispanic. Mother's mean age is 28 years, while father's mean age is 31 years. A little over half of all mothers and fathers never attended college, while two in five mothers and roughly two in five fathers have some college education. On average, mothers began receiving prenatal care in the second month of pregnancy. In terms of insurance coverage, 45% of the births were paid by Medicaid, 49% were covered by private health insurance plans and three percent were covered out of pocket.

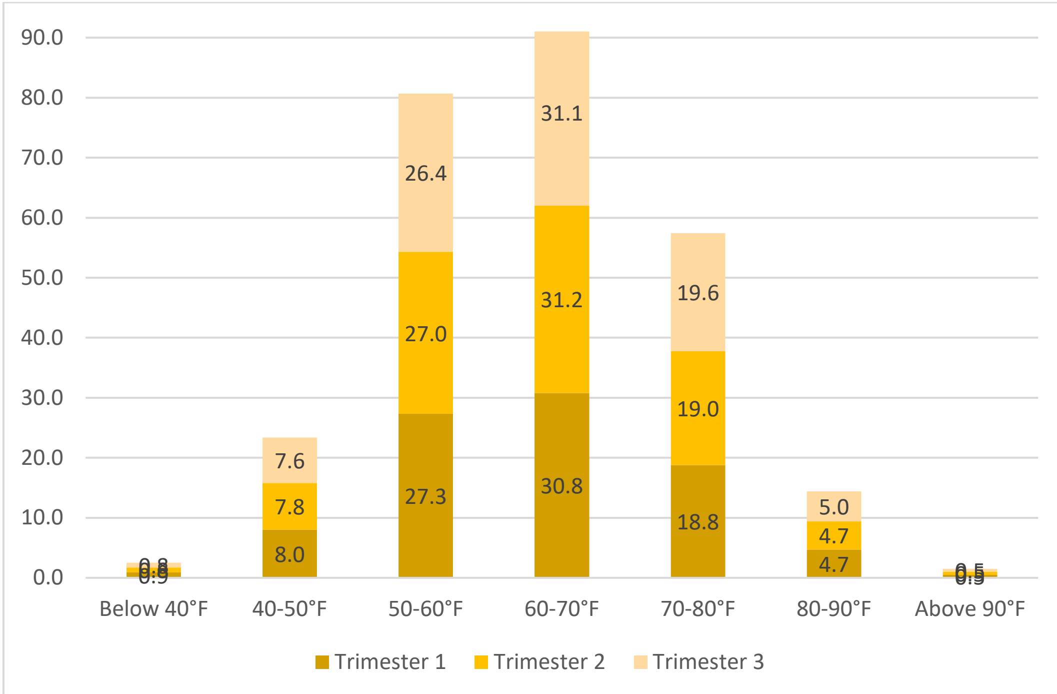
[14] These numbers are in line with national birth weight statistics published by the CDC. Per Table 22 in the National Vital Statistics Reports of 2018 (https://www.cdc.gov/nchs/data/nvsr/nvsr67/nvsr67_08-508.pdf), the mean US birth weight based on births during the period, 2010–2017 is approximately 3227 grams. Auxiliary statistics, such as the principal source of payment for deliveries or the mother's mean age, also parallel national data. National fetal mortality rates average about 6 deaths per 1000 live births plus fetal deaths.

TABLE 1A. DESCRIPTIVE STATISTICS ON IN UTERO EXPOSURE TO TEMPERATURE

Trimester/Bins	Mean	Std deviation	Mean	Std deviation	Mean	Std deviation
	Years: 1991-2011; N = 10970246		Coldest year: 1998; N = 126005		Hottest year: 1996; N = 127716	
Trimester 1						
Below 40°F	0.9	4.2	1	5.7	0.7	3.5
40-50°F	8	13.8	10.5	13.2	6.4	8.5
50-60°F	27.3	22.5	44.1	17.8	31.9	17
60-70°F	30.8	19.7	30.3	18.6	38.5	14.8
70-80°F	18.8	21	3.7	6.7	12	12
80-90°F	4.7	9.4	0.2	1.8	1.3	4.1
Above 90°F	0.5	3.6	0	0.7	0.1	1.1
Trimester 2						
Below 40°F	0.8	4.1	0.1	1.1	0	0.4
40-50°F	7.8	13.6	0.8	3.3	0.3	1.7
50-60°F	27	22.4	10.8	15.3	5.7	12.2
60-70°F	31.2	19.8	35.7	19.8	32.3	20.8
70-80°F	19	20.9	30.9	17.6	39.1	18.9
80-90°F	4.7	9.5	10.9	11.8	12.3	13.7
Above 90°F	0.5	3.7	1.7	6.2	1.4	6.6
Trimester 3						
Below 40°F	0.8	4.1	0.5	2.5	0.2	1.9
40-50°F	7.6	13.5	3.1	6.6	2.4	6
50-60°F	26.4	22.4	17.5	17.1	17.7	17.3
60-70°F	31.1	19.8	36.8	14.7	31.2	17.1
70-80°F	19.6	21.2	23.1	16.3	30.9	20.1
80-90°F	5	9.7	8.7	10.2	7.6	10.3
Above 90°F	0.5	3.9	1.4	4.6	0.9	4.3

Note: Authors' calculations. Bins are based on daily mean temperatures. For each trimester, mean values show the average number of days of prenatal exposure to a given range of daily mean temperatures. The full sample contains over 10 million hospital births between 1991 and 2011. The coldest and hottest years during this period were identified using the average annual temperature in Figure 2.

FIGURE 3. THE DISTRIBUTION OF IN UTERO EXPOSURE BY TRIMESTER AND TEMPERATURE BIN



Note: Prenatal temperature exposure data is taken from Table 1A.

TABLE 1B. DESCRIPTIVE STATISTICS ON NEWBORN HEALTH AND PARENTS

Variable	Mean	Standard deviation	Min	Max
Outcomes				
Birth weight (grams)	3338.60	572.40	261	6000
Gestational age (days)	273.90	14.30	182	294
Fetal death	0.00301	0.05477	0	1
Newborn Characteristics				
Boy	0.51	0.50	0	1
White	0.32	0.47	0	1
Black	0.06	0.24	0	1
Asian	0.10	0.29	0	1
Other races	0.06	0.23	0	1
Hispanic	0.47	0.50	0	1
Single birth	0.97	0.16	0	1
Parent Characteristics				
Mother's age	27.71	6.30	13	49
Father's age	30.52	6.89	13	98
Mother's education				
Less than high school	0.30	0.46	0	1
High school graduate	0.27	0.45	0	1
Some college	0.20	0.40	0	1
Bachelor's and higher degrees	0.21	0.40	0	1
Missing	0.02	0.14	0	1
Father's education				
Less than high school	0.27	0.44	0	1
High school graduate	0.27	0.44	0	1
Some college	0.17	0.37	0	1
Bachelor's and higher degrees	0.21	0.40	0	1
Missing	0.08	0.26	0	1
Primary source of payment				
Medicaid	0.45	0.50	0	1
Private insurance	0.49	0.50	0	1
Self-pay	0.03	0.17	0	1
Other sources	0.02	0.13	0	1
Prenatal care				
Month prenatal care initiated	2.48	1.47	0	9

Note: All variables come from the OSHPD's database of hospital births in California between 1991 and 2011. We cull the raw data for observations missing birth weight, gestational age, date of birth or ZIP code information and then restrict the analysis sample to mothers in the ages of 13-49 who gave birth after at least two full trimesters of pregnancy. We also drop observations with birth weight over 6000 grams; for reference, about 0.1% of all births in the U.S. have a birth weight of 5000 grams or more, according to CDC data (Martin et al. 2018; 2019). Our full analysis sample contains 10,970,246 observations.

3. Empirical Strategy

3.1. Model

We conceptualize temperature as an environmental stressor that determines fetal mortality, birth weight and gestational age. Our empirical model for newborn health and temperatures takes the form in Equation 1:

$$Y_{izt} = \beta_0 + \sum_{j=1}^{7} \beta_j^1 D_{ijzt}^1 + \sum_{j=1}^{7} \beta_j^2 D_{ijzt}^2 + \sum_{j=1}^{7} \beta_j^3 D_{ijzt}^3 + X_{izt} + \alpha_{iz} + \alpha_{it} + \epsilon_{izt} \qquad (1)$$

The dependent variable, Y_{izt}, refers to the birth weight or gestational age of infant i born in ZIP code z on date t. In the event of fetal death, Y_{izt} takes a value of 1 for fetus i in ZIP code z on date t, and 0 otherwise. The independent variable of interest is the temperature exposure during gestation, which we assume lasted three full trimesters. This is represented in the model by the second, third and fourth terms. For example, the variable, D_{ijzt}^1 counts the number of days in the daily mean temperature bin j during the first trimester of infant i born in ZIP code z on date t; variables D_{ijzt}^2 and D_{ijzt}^3 perform a similar function for the infant's exposure during the second and third trimesters, respectively. For any trimester M, there are seven temperature variables since j = 1, …, 7:

$$D_{i1zt}^M = days\ with\ mean\ temperature < 40°\text{F}$$

$$D_{i2zt}^M = days \in [40,50)°\text{F}$$

$$D_{i3zt}^M = days \in [50,60)°\text{F}$$

$$D_{i4zt}^M = days \in [60,70)°\text{F}$$

$$D_{i5z}^M = days \in [70,80)°\text{F}$$

$$D_{i6zt}^M = days \in [80,90)°\text{F}$$

$$D_{i7zt}^M = days\ with\ mean\ temperature > 90°\text{F}$$

By construction, the temperature variables in any trimester M sum to 91 days. To avoid perfect collinearity, we drop D_{i3zt}^1, D_{i3zt}^2 and D_{i3zt}^3 during estimation, implicitly setting β_3^1, $\beta_3^2$and β_3^3 to zero.[15] Estimates of the other β_j^Mcoefficients are compared to the coefficients on these omitted bins. The terms that follow the temperature variables in the model refer to a matrix of demographic and socioeconomic determinants of newborn health (X_{izt}), fixed effects for ZIP

[15] The 50-60°F bin contains California's long-run normal (approximately 58°F) as well as the average annual temperature over the sample period (58.6°F). See Figure 2.

codes (α_{iz}) and fixed effects for the year, month and day of the week of birth (α_{it}). We cluster standard errors at the ZIP code level. The term, X_{izt}, includes various parent attributes in the form of indicators and categorical variables. For example, we code the educational attainments of the mother and father as categorical variables with six levels: less than middle school, more than middle school but less than high school, up to high school, some college, college degree and graduate degree. Likewise, we create seven age-group indicators for mothers and twelve, for fathers. Since father's age is missing in 785,749 cases (7.2% of sample), we impute the median age of fathers to these cases (median is 30 years and the mean is 30.6 years).[16]

3.2. Identification

To identify the causal effect of local ambient temperatures on newborn health, we implement ordinary least squares estimation with ZIP code fixed effects. These fixed effects expunge time-invariant, location-specific attributes that affect newborn health and are correlated with prenatal temperature exposure. For example, elevation above sea level and distance from the coast tend to influence not only how variable a ZIP code's temperatures are but also the socioeconomic composition of a ZIP code's residents. Fixed effects would make the temporal variation in ZIP code temperatures almost random, and plausibly exogenous to any unobserved determinant of newborn health. This empirical framework allows us to estimate the causal relationship of interest by relating, within locations, variations in newborn health to essentially random deviations in local temperature over time.

Although our focus is extreme heat, we also estimate the effects of extreme cold on birth weight with two temperature bins, 40-50°F and under 40°F. We describe "heat" on a more graduated scale, defining four temperature bins above the default bin, with the topmost bin representing days with mean temperature over 90°F. While many parts of inland California routinely top 100°F in the summer months, a mean temperature of 90°F is an extraordinarily hot day since it requires that a high of 100°F be accompanied by a low of at least 80°F. [17] Since only 1% of days over the study period have a daily mean temperature greater than 90°F while 5% of days fall

[16] Since systematic differences in the characteristics of women who conceive in different seasons can confound identification of the thermal effect on health at birth, we subject our eventual findings to a series of robustness checks. These include estimating Equation 1 after (a) omitting all parental characteristics, (b) adding trends in the month of birth to allow the composition of women giving birth in a given month to change over time, and (c) including a trend in each level of mother's education to the initial set of control variables to allow the relationship between mother's education and newborn health to change over time. Our estimates were unchanged in every case. (Results available upon request).

[17] We follow the convention in the literature (e.g. Deschenes et al. 2009, Deschenes and Greenstone 2011) by defining daily mean temperature as the mid-point between the daily high and daily low temperature recognizing that this metric overlooks the temporal distribution of temperature throughout the day.

into the 80-90°F bin (see Figure 3), these bins seem to capture the extreme heat exposure of California's population.

In X_{izt}, our model incorporates controls for the timing and type of birth as well as for the demographic and socioeconomic characteristics of the parents. We indicate if the birth (type) was a singleton, twin, triplet or higher multiples; we specify the sex and race/ethnicity of the infant; we include indicator variables for the age-group and education level of each parent and for whether the birth was covered by Medicaid, private health insurance or borne out-of-pocket; we also control for the first month of pregnancy that the mother sought prenatal care. In the term, α_{it}, we include fixed effects for the year of birth (1991–2011), month of birth (January–December), and day of birth (Monday–Sunday).

In the next section, we present estimates of the temperature impacts on newborn health. We also explore the heterogeneity of temperature impacts by season of conception and conduct robustness checks with an alternative definition of extreme temperatures.

4. Main Results

4.1. Effects on Birth Weight, Gestational Age and Fetal Death

We summarize in utero exposure by sorting the days in each trimester among the seven daily mean temperature bins. In comparison with the literature[18], our bins apply higher thresholds to both extreme cold and extreme heat to better reflect California's climate. Because we omit the 50-60°F bin during estimation, the point estimate of an included bin is the effect of a marginal day in that bin relative to a day in the omitted bin. Table 2 shows the results of regressing birth weight (in grams), gestational age (in days) and fetal death (a binary outcome) on in utero temperature exposure.[19] In columns 1–3, the birth weight regression does not control for gestation whereas in columns 4–6, the birth weight regression controls for gestation. Note that we use the terms "high" ("low") temperature as shorthand for daily mean temperature greater than 60°F (less than 50°F).

Consider the effect of high temperatures on birth weight and gestation. For Trimester 1, we see that high temperatures benefit both birth weight and gestation (columns 1 and 7), and that controlling for gestation (column 4) reduces the estimated benefit to birth weight by 40% or more. For Trimesters 2 and 3, we see that high temperatures are harmful to both birth weight

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[18] See Deschenes et al. (2009) who choose to represent extreme cold using a cut-off of 25°F and extreme heat with a cut-off of 85°F in their study of temperatures and birth weights in the contiguous U.S.

[19] In our data, the station-level correlation between the daily mean and the daily high (daily low) is 0.96 (0.93), due to which we found a very similar pattern of results by expressing in utero exposure on the basis of the daily maximum temperature instead of the daily mean.

and gestation (columns 2-3 and 8-9). Controlling for gestation mostly increases the estimated harm to birth weight in Trimester 2 (column 5) but attenuates it in Trimester 3 (column 6). High temperatures begin to have adverse effects on gestational age in Trimester 2, which intensify in Trimester 3. As column 9 shows, all manner of high temperature days shorten gestation, with impacts increasing monotonically from the 60-70°F bin (–0.003) to the above 90°F bin (–0.009).

Turning attention to the coldest temperatures, we find significant impacts in Trimesters 2 and 3, with the impact being more pronounced in Trimester 3: exposure to daily means below 40°F has positive effects on birth weight and gestation (columns 3 and 9) but the gain in birth weight is fully attributable to a longer gestation (column 6).

Our results comport with patterns reported in the literature. Like Deschenes, Greenstone and Guryan (2009) and Andalón et al. (2016), we find that prenatal heat exposure in the third trimester of pregnancy reduces birth weight. Like the former, we find that second trimester heat is also detrimental to birth weight. Like the latter, we detect a positive relationship between late trimester exposure to extreme cold and gestational age as well as a negative relationship between heat and gestation.

The cumulative thrust of in utero temperature exposure on birth weight is a negative heat effect. Take 1996, the hottest year in our sample. Applying the coefficient estimates in Table 2 to the temperature exposure of the average infant born in that year, we find an average gain of 8.02 grams in the first trimester, followed by a loss of 22.06 grams in the second trimester and 9.09 grams in the third trimester. The cumulative temperature impact on the birth weight of 1996 newborns is a loss of 23.12 grams relative to the whole sample average. Alternatively, take 1998, our coldest sample year. In the first trimester, thermal exposure adds 5.1 grams to the fetus, but takes away 20 grams and 8.6 grams through the second and third trimesters, respectively, leaving behind an average loss of 23.55 grams relative to the full sample mean.

Our analysis compares pregnancy outcomes in ZIP codes with different degrees of temperature variation to identify temperature impacts. This requires a stable composition of mothers in different ZIP codes so we do not confound changes in temperature with changes in maternal characteristics over time. We find evidence to support this assumption; specifically, we find that ZIP codes with the greatest and least temperature variation exhibit similar compositional changes over the sample period; parents are older, more educated, more likely to be covered by Medicaid and to seek prenatal care earlier in pregnancies. Thus, we find no evidence that our sample contained differential sorting of mothers across ZIP codes or over time.

Finally, in columns 10–12, we investigate the impact of extreme temperatures on fetal death. While no thermal effect is apparent in the first trimester, there is an increase in fetal death from second and third trimester exposures. Notably, in seven out of the nine cells where we detect a negative temperature impact on birth weight, we find a positive temperature impact on fetal death. Two inferences follow: first, our thermal impact on birth weight is an underestimate. Inasmuch as extreme heat culls fetuses that might be born with very low birth weight, the surviving sample is positively selected. Second, there is evidence in the medical literature (Dreier et al. 2014; Pei et al. 2015; Van Zutphen et al. 2012; Asamoah et al. 2018) that maternal hyperthermia is especially teratogenic in the first trimester and can lead to fetal death. This biological shock response to extreme heat can explain why we detect an apparent beneficial first trimester heat effect on the birth weight of surviving newborns.

Does Pollution Confound Temperature?

Until now, our analysis has not accounted for the role of air pollution or other weather phenomena in newborn health. As an omitted variable correlated with both health at birth as well as temperature, air pollution is potentially a major confound in our analysis. Below, we perform a robustness check of our thermal impact estimates by controlling for air pollutants and meteorological variables known to vary with temperature and to affect newborn health.

Under the Clean Air Act, the US EPA sets what is known as the National Ambient Air Quality Standards (NAAQS) for six criteria pollutants: ozone, carbon monoxide, sulphur dioxide, nitrogen dioxide, ozone, lead and particulate matter. We collect county-by-year data on ozone (a criteria pollutant), county-by-year data on ambient air quality (AQI), and ZCTA-level yearly precipitation data. We select ozone as a confounder of interest because it is distinctly reactive to temperature (Belan, Savkin and Tolmachev 2018; Shen, Mickley and Gilleland 2016). We select the AQI because it subsumes all criteria pollutants. We select rainfall because studies have shown that positive rainfall shocks redound to health at birth as well as later-life well-being (Rocha and Soares 2015; Maccini and Yang 2009) while drought increases in utero malnutrition and infant mortality (Kudamatsu, Persson and Strömberg 2012). Moreover, data on humidity is sparser than data on rainfall while standing water and other forms of precipitation are less common in California, and therefore, less relevant in our sample.

All ambient air pollution data are available via the Air Quality System repository of the US EPA. We utilize the pre-generated annual summary data on monitor-level concentrations of tropospheric ozone and county-level AQI for this analysis. The AQI runs from 0 to 500 and the higher the value, the greater the level of air pollution and the greater the health concern. For each criteria pollutant, an AQI value of 100 generally corresponds to an ambient air concentration that equals the level of the short-term NAAQS. Thus, AQI values at or below 100 are generally thought of as satisfactory. We calculate the percentage of days with AQI under 100 for each county-year and assign prenatal exposure according to the infant's county of residence and year(s) spanned by their gestation period. In a similar manner, we assign prenatal exposure using county-by-year (58 counties over 21 years) data on ozone from the US EPA. Finally, to evaluate if moisture is a confounder, we calculate exposure to rainfall at the infant's ZCTA. Rainfall data is available via the GHCN-Daily product, NOAA's archive of all types of meteorological elements at different spatial resolutions We access data on the PRCP element at the ZIP code level for the years 1990 through 2012.

At the outset, we do not expect pollution – or moisture – to threaten our internal validity. This is because we identify the thermal effect on newborn health off deviations from ZCTA-year–specific averages. While ground-level ozone concentrations are correlated with temperature in any given area, they are less likely to be correlated with mean deviations of local temperature. A review of the literature on ambient air pollution and pregnancy outcomes by Šrám et al. (2005) as well as a study using California ZIP code data by Morello-Frosch et al. (2010) find that maternal exposure to air pollution could result in modestly lower infant birth weight but that these impacts are small.

In Table 3, we show estimates of the temperature impact on birth weight, gestational age and fetal death in four panels. As in Table 2, we regress each outcome on in utero temperature exposure but this time, we also control for exposure to tropospheric ozone, ambient air quality and rainfall simultaneously.[20] In every panel of Table 3, we find that our estimates are highly robust to the inclusion of these potential confounders. There is neither any attenuation to the point estimates nor any change in sign. Fewer than half of the twenty-one coefficients in the birth weight panels see a change, and none of the changes is larger than 0.02 in magnitude. We continue to see a significant, negative relationship between heat and gestation in the third trimester, as well as a significant, positive relationship between heat and fetal death in the second and third trimesters.

Our results are not unique. Evaluating the association between apparent temperature and the risk of stillbirth in a sample of 8,500 California fetal deaths, Basu, Sarovar and Malig (2016) test for confounding as well as effect modification by four criteria pollutants (sulphur dioxide, carbon monoxide, nitrogen dioxide and ozone). However, they find neither. In an older study linking apparent temperature to the risk of preterm delivery in a sample of 60,000 California births, Basu, Malig and Ostro (2010) report that no pollutant demonstrated confounding or even an independently significant, positive association with preterm delivery.

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[20] We also investigated confounding by air pollution and moisture by entering these controls one at a time in the birth weight regression instead of all at once. We obtained virtually identical results to Table 3. Similar checks were performed with the outcomes of gestational age and fetal death. (Results available upon request).

4.2. Timing of Conception

Exposure to extreme temperatures is dictated not only by location, but also by the quarter of conception. To analyze how the timing of conception shapes the temperature gradients in birth weight, we divide our 11 million births into four sub-samples by considering which months of conception produce the hottest possible first, second and third trimester or even no "extremely hot" trimester.

As described in section 2.3, babies conceived in the months of September, October and November are unlikely to be exposed to the hottest time of the year in California, which are typically the months of July and August. All other babies, assuming full term, are exposed to these months at some stage of gestation. For example, a baby conceived in December, January, or February will confront the hottest months in its third trimester; a baby conceived in March, April, or May will confront them in its second trimester and a baby conceived in June, July, or August will experience these months in its first trimester. In Table 4, we show the results from implementing the birth weight regression without controlling for gestation in each of these sub-samples.

For Trimester 1, we can examine how high and low temperatures affect birth weight using columns 1, 4, 7 and 10. Take high temperature days first. These include warm days (60-70°F), very warm days (70-80°F), hot days (80-90°F) and extremely hot days (above 90°F). In utero exposure to days in any of these bins has a positive impact on birth weight for babies conceived in Sep-Oct-Nov or in June-July-August (columns 1 and 10) but negative impacts on birth weight for babies conceived in the other months (columns 4 and 7). Essentially, when Trimester 1 overlaps with the winter or spring, high temperatures hurt birth weight. It is clear from columns 4 and 7 that the hotter the day, the greater the loss of birth weight. Lost birth weight per day of exposure ranges between 4 and 13 grams for babies conceived in the winter months of December through February (column 4), and between 5 and 11 grams for babies conceived in the spring months of March through May (column 7). In contrast, the effect of high temperature days in Trimester 1 for babies conceived in September, October or November (column 1) is not only positive but increasing in the mean temperature. A warm day increases birth weight by 9 grams while an extremely hot day increases it by 17 grams. For babies conceived in the summer (column 10), exposure to high temperature days in Trimester 1 is again beneficial; in this sub-sample, the birth weight gain is as large as 5.6 grams per very warm day.

Next, we consider the impact of high temperature events in Trimester 2. Once again, we find that there are negative impacts when Trimester 2 overlaps with winter or spring (columns 2 and 5 respectively) but there are positive impacts when Trimester 2 overlaps or follows the summer season (columns 8 and 11 respectively). Babies conceived in the months of September through

November confront winter in Trimester 2; high temperatures at this juncture (column 2) only harm birth weight: exposure to a warm day leads to a loss of 3.4 grams; exposure to a hot day leads to a loss of 12.2 grams and exposure to even one extremely hot day more than doubles the loss to 26 grams. This pattern is echoed in column 5 for babies conceived in the winter and facing a relatively cool season in Trimester 2.

Last, we examine high temperatures in Trimester 3. In keeping with the pattern so far, we find that high temperatures harm birth weight when Trimester 3 coincides with the winter or spring seasons (columns 3 and 12 respectively) but benefit birth weight when Trimester 3 overlaps or follows the summer season (columns 6 and 9 respectively). Babies conceived in June through August (column 12) register the largest adverse effect from extreme heat: they lose 35.6 grams from exposure to an extremely hot day during Trimester 3.

Irrespective of the stage of gestation coinciding, high temperatures in the winter and spring have strong, negative effects on birth weight whereas high temperatures in the summer and autumn have either muted or positive effects.

In Figure 4, we plot the typical range of temperatures by month for all sample ZCTAs. It is clear that what we designate as high temperatures (days in and above the 60-70°F bin) fall outside of the box-plots for the months of November, December and January through April. This suggests that unseasonably high temperatures act as shocks in utero.

We notice a similar tendency with the impact of low temperatures – days in the 40-50°F bin and days in the below 40°F bin – on birth weight. In Trimester 1, low temperatures are almost uniformly harmful to birth weight (columns 1, 4, 7 and 10), with the deepest impact occurring in the case of babies whose first trimester coincides with the summer (column 10). In Trimester 2, low temperatures again affect babies whose second trimester coincides with summer, viz. those who were conceived in March through May (column 8). By contrast, low temperatures in Trimester 3 appear to positively affect nearly all babies, particularly if their third trimester coincides with winter or spring (columns 3 and 12). To summarize, in utero exposure to cold days is detrimental to the fetus, the earlier they occur in gestation and the more anomalous they are for the season overlapping with a given trimester.

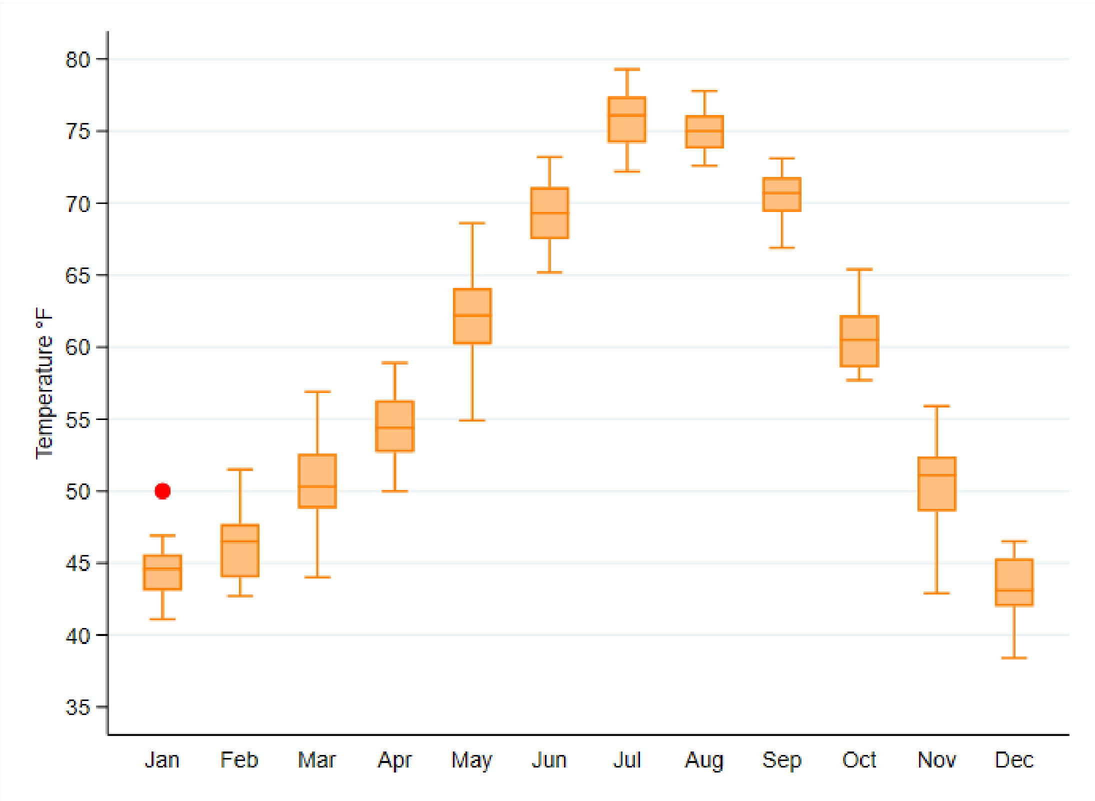
In Table 5, we present the temperature-gestation regressions by season of conception using the same four sub-samples as Table 4.[21] The impact of high temperatures on the gestation channel are virtually similar to the impacts on the birth weight channel. For any trimester, we see that exposure to high temperature days lengthens gestation if the trimester coincides with or follows

[21] An analysis of temperature and fetal death by season of conception is available in Appendix Table A4.

summer (columns 1 and 10 for Trimester 1; columns 8 and 11 for Trimester 2; columns 6 and 9 for Trimester 3) but shortens gestation if the trimester coincides with or follows winter (columns 4 and 7 for Trimester 1; columns 2 and 5 for Trimester 2; columns 3 and 12 for Trimester 3). In Trimester 1 as well as Trimester 2, exposure to low temperatures curtails gestation, more so when the trimester overlaps with summer (columns 8 and 10). In Trimester 3, extreme cold is good for gestation, especially for babies conceived in the last third of the year (column 3).

A consistent picture emerges from analyzing temperature impacts on newborns by season of conception: at any stage of gestation, extreme highs and lows of temperature have adverse impacts when they are atypical for the calendar month in question. The impact of extreme heat is negative in the winter and similarly, the impact of extreme cold is negative in the summer, irrespective of the trimester featured in these seasons. The negative impacts of heat also linger into the following trimester but are not as severe.

FIGURE 4. MONTHLY TEMPERATURES IN CALIFORNIA, 1990-2012



Note: Temperature data comes from the NOAA National Centers for Environmental Information, Climate at a Glance: Statewide Time Series, published February 2020, retrieved on February 27, 2020, from https://www.ncdc.noaa.gov/cag/. The box-plot shows the median, first and third quartiles of monthly temperatures across California ZIP code areas over the sample period. Red circles mark outliers in the monthly data.

TABLE 2. TEMPERATURE IMPACTS ON BIRTH WEIGHT, GESTATION AND FETAL DEATH

Dependent Variable:	**Birth weight (grams)**			**Birth weight (grams)**			**Gestation length (days)**			**Fetal death**		
	Trimester 1	Trimester 2	Trimester 3	Trimester 1	Trimester 2	Trimester 3	Trimester 1	Trimester 2	Trimester 3	Trimester 1	Trimester 2	Trimester 3
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Below 40°F	-0.10	0.05	0.15*	-0.12	-0.05	-0.07	0.0016	0.0055**	0.0124**	-0.000010	0.000018**	-0.000004
	(0.06)	(0.06)	(0.07)	(0.06)	(0.05)	(0.06)	(0.0020)	(0.0017)	(0.0023)	(0.000007)	(0.000005)	(0.000007)
40-50°F	0.04	-0.10**	-0.07*	0.07**	-0.10**	0.07**	-0.0008	-0.0004	-0.0068**	0.000003	0.000006*	0.000005
	(0.03)	(0.03)	(0.03)	(0.02)	(0.02)	(0.02)	(0.0008)	(0.0007)	(0.0009)	(0.000003)	(0.000002)	(0.000003)
60-70°F	0.13**	-0.20**	-0.07**	-0.03	-0.18**	-0.00	0.0079**	-0.0022**	-0.0031**	0.000002	0.000008**	0.000006*
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.0007)	(0.0007)	(0.0008)	(0.000002)	(0.000003)	(0.000002)
70-80°F	0.22**	-0.28**	-0.15**	-0.02	-0.29**	-0.04	0.0120**	-0.0009	-0.0057**	0.000001	0.000010**	0.000006*
	(0.03)	(0.03)	(0.03)	(0.02)	(0.02)	(0.02)	(0.0010)	(0.0010)	(0.0010)	(0.000003)	(0.000003)	(0.000003)
80-90°F	0.13**	-0.36**	-0.28**	0.07	-0.23**	-0.12**	0.0028*	-0.0078**	-0.0087**	0.000001	0.000016**	0.000010*
	(0.04)	(0.04)	(0.04)	(0.04)	(0.03)	(0.03)	(0.0014)	(0.0012)	(0.0013)	(0.000004)	(0.000004)	(0.000004)
Above 90°F	0.23**	-0.14*	0.00	0.11	-0.16**	0.19**	0.0060*	-0.0001	-0.0089**	0.000009	0.000013	0.000012
	(0.08)	(0.07)	(0.08)	(0.07)	(0.05)	(0.07)	(0.0025)	(0.0024)	(0.0022)	(0.000009)	(0.000008)	(0.000008)
Observations:		10,970,246			10,970,246			10,970,246			10,970,246	
Control for gestation?		No			Yes			Not applicable			No	

<u>Note</u>: Cells report estimates of the temperature impact on fetal and infant health by bin and trimester. Standard errors, clustered at ZIP codes, are shown in parentheses. ** p<1%. * p<5%. The dependent variables are infant birth weight (in grams), gestational age (measured in number of days) and fetal death (a binary outcome). The first birth weight regression does not control for gestational age. Control variables in each regression include fixed effects for the location of birth (i.e. ZIP code fixed effects), the timing of birth, type of birth, the infant's sex and race, each parent's age-group and schooling attainment, as well as indicators for health insurance coverage and prenatal care usage. Fixed effects for the timing of birth refer to the day of the week, month and year of birth. Fixed effects for the type of birth indicate if a birth was singleton, twin, triplet, quadruplet, quintuplet or more. Controls for health insurance are indicators for Medicaid/self-paying/other insurance; the omitted category is private insurance. Controls for prenatal care are indicators for the pregnancy month when the mother first sought care.

TABLE 3. TEMPERATURE IMPACTS UNCONFOUNDED BY AIR POLLUTION AND PRECIPITATION

Dependent Variable:	**Birth weight (grams)**			**Birth weight (grams)**			**Gestation length (days)**			**Fetal death**		
	Trimester 1	Trimester 2	Trimester 3	Trimester 1	Trimester 2	Trimester 3	Trimester 1	Trimester 2	Trimester 3	Trimester 1	Trimester 2	Trimester 3
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Below 40°F	-0.05	0.08	0.20**	-0.09	-0.04	-0.05	0.0028	0.0061**	0.0136**	-0.000013	0.000017**	-0.000008
	(0.06)	(0.06)	(0.07)	(0.06)	(0.05)	(0.06)	(0.0021)	(0.0017)	(0.0023)	(0.000007)	(0.000005)	(0.000007)
40-50°F	0.04	-0.09**	-0.07*	0.07**	-0.10**	0.07**	-0.0008	-0.0004	-0.0069**	0.000004	0.000006*	0.000006*
	(0.03)	(0.03)	(0.03)	(0.02)	(0.02)	(0.02)	(0.0008)	(0.0007)	(0.0009)	(0.000003)	(0.000002)	(0.000003)
60-70°F	0.13**	-0.19**	-0.06*	-0.02	-0.17**	0.01	0.0081**	-0.0021**	-0.0030**	0.000001	0.000008**	0.000005*
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.0007)	(0.0007)	(0.0007)	(0.000002)	(0.000003)	(0.000002)
70-80°F	0.22**	-0.28**	-0.15**	-0.01	-0.29**	-0.03	0.0119**	-0.0010	-0.0059**	0.000001	0.000010**	0.000006*
	(0.03)	(0.03)	(0.03)	(0.02)	(0.02)	(0.02)	(0.0010)	(0.0010)	(0.0010)	(0.000003)	(0.000003)	(0.000003)
80-90°F	0.14**	-0.34**	-0.27**	0.08*	-0.22**	-0.10**	0.0030*	-0.0075**	-0.0085**	0.000000	0.000016**	0.000010*
	(0.04)	(0.04)	(0.04)	(0.04)	(0.03)	(0.03)	(0.0014)	(0.0012)	(0.0013)	(0.000004)	(0.000004)	(0.000004)
Above 90°F	0.22**	-0.16*	-0.01	0.10	-0.17**	0.18**	0.0057*	-0.0003	-0.0091**	0.000009	0.000013	0.000013
	(0.08)	(0.07)	(0.08)	(0.07)	(0.05)	(0.07)	(0.0025)	(0.0024)	(0.0022)	(0.000009)	(0.000008)	(0.000008)
Observations:		10,970,246			10,970,246			10,970,246			10,970,246	
Controls												
Ozone		Yes			Yes			Yes			Yes	
Air quality index		Yes			Yes			Yes			Yes	
Rainfall		Yes			Yes			Yes			Yes	
Gestation		No			Yes			Not applicable			No	

Note: Cells report estimates of the temperature impact on fetal and infant health by bin and trimester. Standard errors, clustered at ZIP codes, are shown in parentheses. ** p<1%. * p<5%. The dependent variables are infant birth weight, gestational age and fetal death. The first birth weight regression does not control for gestational age. In addition to the baseline set of control variables, each regression also controls for county-year concentrations of ground-level ozone, county-year ambient air quality and annual rainfall at ZIP codes. Data on ozone and AQI come from the US EPA. Rainfall data is from NOAA. See text for more details.

TABLE 4. THE IMPACT OF TEMPERATURE ON BIRTH WEIGHT BY TIMING OF CONCEPTION

Dependent Variable:	**Birth weight (grams)**											
Conceived during:	Sep/Oct/Nov			Dec/Jan/Feb			March/Apr/May			June/July/Aug		
Coincides with:		Winter		Winter		Summer		Summer		Summer		Winter
	Trimester1	Trimester2	Trimester3	Trimester1	Trimester2	Trimester3	Trimester1	Trimester2	Trimester3	Trimester1	Trimester2	Trimester3
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Below 40°F	-1.12**	-2.05**	8.19**	-3.13**	1.65	-2.80	3.97**	-6.21**	3.46**	-12.18**	1.08**	3.43**
	(0.40)	(0.33)	(1.00)	(0.39)	(0.97)	(1.68)	(0.95)	(1.12)	(0.29)	(1.08)	(0.32)	(0.29)
40-50°F	-1.08**	-0.91**	2.78**	-0.71**	0.21	2.60**	-1.33*	-5.88**	0.63***	-9.10**	-0.80**	1.15**
	(0.15)	(0.13)	(0.53)	(0.17)	(0.68)	(0.75)	(0.53)	(0.68)	(0.15)	(0.86)	(0.17)	(0.13)
60-70°F	8.90**	-3.39**	-6.06**	-3.58**	-9.78**	4.27**	-5.08**	4.01**	7.38**	4.51**	10.64**	-4.61**
	(0.15)	(0.10)	(0.17)	(0.12)	(0.20)	(0.27)	(0.12)	(0.31)	(0.16)	(0.49)	(0.16)	(0.12)
70-80°F	11.77**	-8.20**	-9.03**	-9.30**	-14.94**	7.95**	-8.21**	5.89**	10.90**	5.60**	14.78**	-6.21**
	(0.16)	(0.22)	(0.22)	(0.22)	(0.26)	(0.28)	(0.15)	(0.33)	(0.15)	(0.49)	(0.18)	(0.22)
80-90°F	11.81**	-12.16**	-7.89**	-12.83**	-11.58**	7.37**	-7.18**	5.08**	12.42**	3.31**	14.66**	-7.32**
	(0.38)	(0.61)	(0.29)	(0.64)	(0.31)	(0.29)	(0.21)	(0.34)	(0.29)	(0.52)	(0.34)	(0.85)
Above 90°F	17.31**	-25.97**	-6.47**	-4.39	-14.46**	10.49**	-10.90**	5.12**	14.92**	1.49**	15.71**	-35.62**
	(1.76)	(6.57)	(0.42)	(3.15)	(0.36)	(0.47)	(0.48)	(0.45)	(1.20)	(0.56)	(1.41)	(4.69)
Observations	2,805,224			2,778,519			2,691,747			2,694,756		

Note: Cells report estimates of the temperature impact on birth weight by bin and trimester. Standard errors, clustered at ZIP codes, are shown in parentheses. ** p<1%. * p<5%. The dependent variable is infant birth weight (in grams). Regressions do not control for gestational age. Control variables used in all regressions include fixed effects for the location of birth (i.e. ZIP code fixed effects), the timing of birth, type of birth, the infant's sex and race, each parent's age-group and schooling attainment, as well as indicators for health insurance coverage and prenatal care usage. Fixed effects for the timing of birth refer to the day of the week, month and year of birth. Fixed effects for the type of birth indicate if a birth was singleton, twin, triplet, quadruplet, quintuplet or more. Controls for health insurance are indicators for Medicaid/self-paying/other insurance; the omitted category is private insurance. Controls for prenatal care are indicators for the pregnancy month when the mother first sought care.

TABLE 5. THE IMPACT OF TEMPERATURE ON GESTATION BY TIMING OF CONCEPTION

Dependent Variable:	**Gestation length (days)**											
Conceived during:	Sep/Oct/Nov			Dec/Jan/Feb			March/Apr/May			June/July/Aug		
Coincides with:		Winter		Winter		Summer		Summer		Summer		Winter
	Trimester1	Trimester2	Trimester3	Trimester1	Trimester2	Trimester3	Trimester1	Trimester2	Trimester3	Trimester1	Trimester2	Trimester3
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Below 40°F	-0.05*	-0.12**	0.45**	-0.17**	0.07	-0.17*	0.20**	-0.33**	0.22**	-0.68**	0.09**	0.18**
	(0.02)	(0.02)	(0.06)	(0.02)	(0.05)	(0.08)	(0.06)	(0.05)	(0.02)	(0.05)	(0.02)	(0.01)
40-50°F	-0.06**	-0.05**	0.16**	-0.04**	0.01	0.10**	-0.09**	-0.36**	0.04**	-0.56**	-0.04**	0.06**
	(0.01)	(0.01)	(0.03)	(0.01)	(0.03)	(0.04)	(0.03)	(0.04)	(0.01)	(0.05)	(0.01)	(0.01)
60-70°F	0.49**	-0.20**	-0.34**	-0.20**	-0.52**	0.26**	-0.28**	0.24**	0.40**	0.27**	0.59**	-0.26**
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.01)	(0.03)	(0.01)	(0.01)
70-80°F	0.64**	-0.49**	-0.50**	-0.53**	-0.79**	0.47**	-0.46**	0.36**	0.59**	0.33**	0.83**	-0.34**
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.01)	(0.02)	(0.01)	(0.03)	(0.01)	(0.01)
80-90°F	0.64**	-0.69**	-0.43**	-0.76**	-0.60**	0.44**	-0.40**	0.31**	0.66**	0.19**	0.82**	-0.41**
	(0.02)	(0.03)	(0.02)	(0.03)	(0.02)	(0.02)	(0.01)	(0.02)	(0.01)	(0.03)	(0.02)	(0.05)
Above 90°F	0.88**	-1.53**	-0.35**	-0.31**	-0.76**	0.59**	-0.64**	0.31**	0.76**	0.08**	0.90**	-2.01**
	(0.08)	(0.24)	(0.02)	(0.12)	(0.02)	(0.03)	(0.02)	(0.02)	(0.05)	(0.03)	(0.07)	(0.27)
Observations	2,805,224			2,778,519			2,691,747			2,694,756		

Note: Cells report estimates of the temperature impact on gestational age by bin and trimester. Standard errors, clustered at ZIP codes, are shown in parentheses. ** p<1%. * p<5%. The dependent variable is gestational age (measured in number of days). Control variables include fixed effects for the location of birth (i.e. ZIP code fixed effects), the timing of birth, type of birth, the infant's sex and race, each parent's age-group and schooling attainment, as well as indicators for health insurance coverage and prenatal care usage. Fixed effects for the timing of birth refer to the day of the week, month and year of birth. Fixed effects for the type of birth indicate if a birth was singleton, twin, triplet, quadruplet, quintuplet or more. Controls for health insurance are indicators for Medicaid/self-paying/other insurance; the omitted category is private insurance. Controls for prenatal care are indicators for the pregnancy month when the mother first sought care.

4.3. Sensitivity Checks

One challenge in evaluating the impact of temperatures on health is in the representation of individual exposure. Temperature bins are one way of allowing for non-linear impacts and are common in the literature. Yet, there is little guidance scientifically as to how the bins should be defined. In the above analysis, we chose our temperature bins non-parametrically to reflect the wide range of climates throughout California.[22] To investigate the sensitivity of this approach, we estimate in Table 6, the impact of temperature on birth weight, gestational age and fetal death using the bin design in Deschenes, Greenstone and Guryan (2009).

Our results are robust to this alternate design, even though the new bins are significantly different from our initial definition and not especially apt for California. First, the new bins are twice as wide as ours. Second, the omitted temperature bin in the regression is 45-65°F. Set against the distribution in Figure 4, a daily mean temperature of 45°F registers as extreme cold whereas a daily mean temperature of 65°F is about the historical average. Third, days in the lowest bin (mean temperatures under 25°F) are rare in California whereas days in the highest bin (mean temperatures over 85°F) are not uncommon in several ZIP codes. This works into the precision of the estimates associated with these bins: notice that the standard error on the bottom bin in Table 6 is at least six times as large as the standard error on the top bin.

While these differences may seem significant, the pattern of results in Tables 2 and 6 are very similar. Extreme heat increases birth weight in the first trimester, reduces it in the second trimester, and reduces it (but to a smaller extent) in the third trimester. Controlling for gestation in the birth weight regression deflates the negative impacts, reflecting the negative relationship between extreme heat and gestation in the second and third trimesters. Extreme cold shows a positive effect on birth weight and gestation after the first trimester. The risk of fetal death rises with heat exposure in the second trimester but is otherwise unaffected by temperature.

[22] For instance, the California Energy Commission defines 16 building climate zones for the state: https://ww2.energy.ca.gov/maps/renewable/building_climate_zones.html

TABLE 6. ROBUSTNESS CHECK: ALTERNATE TEMPERATURE BINS

Dependent Variable:	Birth weight (grams)			Birth weight (grams)			Gestation length (days)			Fetal death		
	Trimester 1	Trimester 2	Trimester 3	Trimester 1	Trimester 2	Trimester 3	Trimester 1	Trimester 2	Trimester 3	Trimester 1	Trimester 2	Trimester 3
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Below 25°F	-0.76	1.14**	0.16	-0.23	0.75*	-0.37	-0.0195	0.0287**	0.0382*	-0.000030	-0.000020	-0.000017
	(0.39)	(0.41)	(0.60)	(0.41)	(0.29)	(0.40)	(0.0210)	(0.0106)	(0.0162)	(0.000038)	(0.000031)	(0.000040)
25-45°F	0.01	0.02	0.07	0.05	-0.08*	0.06	-0.0007	0.0044**	0.0006	-0.000003	0.000007*	0.000002
	(0.04)	(0.03)	(0.04)	(0.03)	(0.03)	(0.04)	(0.0011)	(0.0010)	(0.0011)	(0.000004)	(0.000003)	(0.000004)
65-85°F	0.14**	-0.20**	-0.14**	0.01	-0.21**	-0.05**	0.0067**	-0.0006	-0.0047**	-0.000002	0.000007**	0.000004
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.0007)	(0.0006)	(0.0006)	(0.000002)	(0.000002)	(0.000002)
Above 85°F	0.17**	-0.18**	-0.14*	0.23**	-0.12**	0.06	-0.0028	-0.0033*	-0.0101**	-0.000002	0.000010*	0.000005
	(0.06)	(0.04)	(0.06)	(0.05)	(0.03)	(0.05)	(0.0019)	(0.0013)	(0.0016)	(0.000006)	(0.000005)	(0.000005)
Observations:		10,970,246			10,970,246			10,970,246			10,970,246	
Control for gestation?		No			Yes			Not applicable			No	

Note: Cells report estimates of the temperature impact on fetal and infant health by bin and trimester. Standard errors, clustered at ZIP codes, are shown in parentheses. ** p<1%. * p<5%.

5. Conclusion

With long-term evidence indicating robust warming over the past century and increases in the number of unusually hot days (Horton et al. 2015; IPCC 2014), increased attention is being given to the role of extreme weather events on health outcomes. Our study contributes to this research by investigating the relationship between health at birth and in utero exposure to extreme temperatures in a California sample. As with prior research, we find that extreme heat exerts positive and negative effects on birth weight, depending on the stage of gestation and the season in which the extreme temperature event occurs. In general, extreme heat is beneficial in the first trimester, most harmful in the second trimester and somewhat harmful in the third trimester. The positive first trimester effect of heat on birth weight may be the fall-out of a selection effect we cannot comprehensively test. The medical literature (Dreier et al. 2014; Pei et al. 2015; Van Zutphen et al. 2012; Asamoah et al. 2018) shows that maternal hyperthermia is especially teratogenic in the first trimester. If a number of first trimester miscarriages are triggered by maternal hyperthermia, it would skew the observed sample of newborns towards the heavier end of the birth weight scale, thereby giving the appearance of a beneficial first trimester heat effect. In contrast to the effects of extreme heat, extreme cold does not appear to affect birth weight until the third trimester of pregnancy.

Significantly, we find that the birth weight impacts of extreme temperatures are amplified when the extreme temperature event is anomalous for the prevailing season. When we disaggregate the sample by season of conception, our results suggest that extreme heat has more detrimental effects during cool seasons than warm seasons while extreme cold is more harmful in warm seasons than cool. This pattern holds regardless of the trimester that is overlapping.

With respect to gestational age, we find that the effects of extreme heat and extreme cold are concentrated in the third trimester. Although we do not examine the effect of extreme temperatures on preterm birth directly, our results for gestation suggest that extreme temperatures would make preterm births more likely.

In Appendix Table A5, we make a brief foray into the mechanisms behind our results: Although we lack data on parent income and distress, we can test if thermal impacts on infant health differ by parental education. We hypothesize that indirect effects of temperatures, if any, should be larger among less-educated parents as they may have less resources to protect against weather extremes. We test this hypothesis by running the birth weight regression in two sub-samples: one where neither parent went to college and another where at least one parent went to college. However, estimates turn out to be quite similar at different levels of education, so we conclude that thermal impacts on newborn health in our sample stem less from socioeconomic status than biological responses to extreme temperatures during pregnancy.

By showing how extreme temperature events impinge on the health of future generations, our results provide additional evidence for urgent action on climate change.

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Appendix

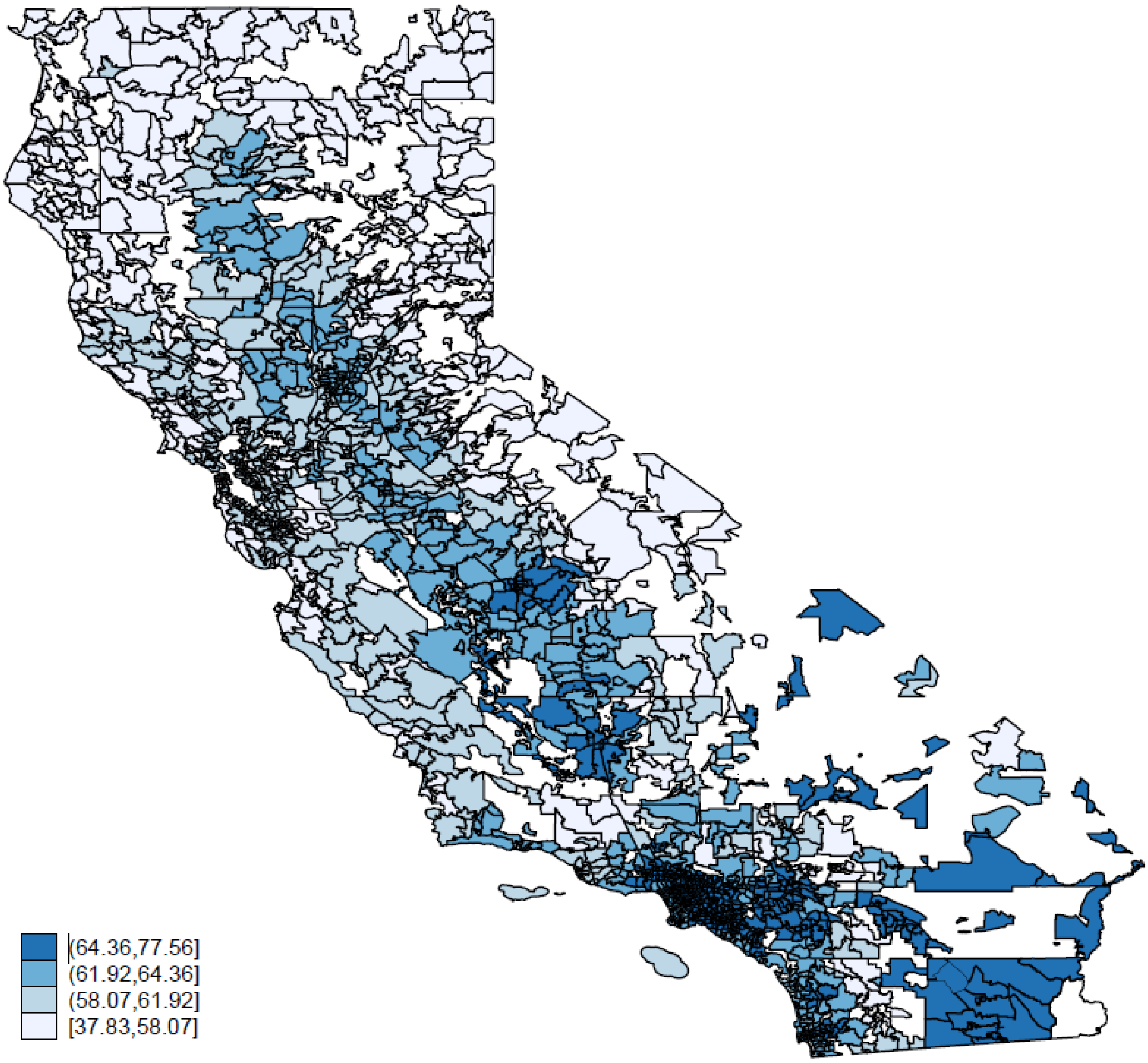
TABLE A1. DAILY TEMPERATURE DATA OF ZIP CODE TABULATION AREAS

ZCTA days with	**Year**									
	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Missing temperature data	0.08	0.05	0.13	0.03	0.08	0.04	0.13	0.23	0.06	0.02
Temperature data from the										
Nearest station	92.00	92.00	91.00	93.00	93.00	93.00	92.00	91.00	94.00	94.00
Second-nearest station	7.50	7.60	7.90	6.70	6.70	6.70	7.10	7.90	6.00	5.90
Third-nearest station	0.50	0.56	0.66	0.42	0.42	0.47	0.58	0.96	0.36	0.30
Temperature data from a station										
Within 10 miles	77.00	78.00	78.00	79.00	79.00	80.00	81.00	82.00	84.00	84.00
Over 10, under 15 miles	16.00	16.00	15.00	15.00	15.00	14.00	14.00	13.00	12.00	11.00
Over 15, under 20 miles	5.20	4.70	5.20	4.80	4.60	4.40	4.10	3.90	3.70	3.30
Over 20, under 25 miles	0.89	0.72	0.87	0.76	0.86	0.71	0.68	0.57	0.51	0.50
Over 25, under 50 miles	0.71	0.48	0.53	0.40	0.34	0.29	0.42	0.39	0.49	0.35

ZCTA days with	**Year**										
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Missing temperature data	0.03	0.07	0.03	0.04	0.04	0.03	0.01	0.06	0.04	0.02	0.02
Temperature data from the											
Nearest station	94.00	92.00	93.00	94.00	93.00	94.00	94.00	93.00	94.00	94.00	95.00
Second-nearest station	6.00	6.80	6.00	5.80	6.60	5.70	5.60	6.20	5.60	5.40	4.60
Third-nearest station	0.37	0.66	0.60	0.35	0.37	0.40	0.32	0.46	0.28	0.41	0.30
Temperature data from a station											
Within 10 miles	85.00	85.00	86.00	86.00	86.00	85.00	86.00	85.00	86.00	86.00	86.00
Over 10, under 15 miles	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00
Over 15, under 20 miles	3.20	2.70	2.50	2.50	2.50	2.60	2.40	2.50	2.50	2.40	2.20
Over 20, under 25 miles	0.67	0.68	0.66	0.63	0.70	0.55	0.53	0.59	0.45	0.42	0.60
Over 25, under 50 miles	0.24	0.23	0.19	0.15	0.15	0.15	0.14	0.15	0.12	0.08	0.08

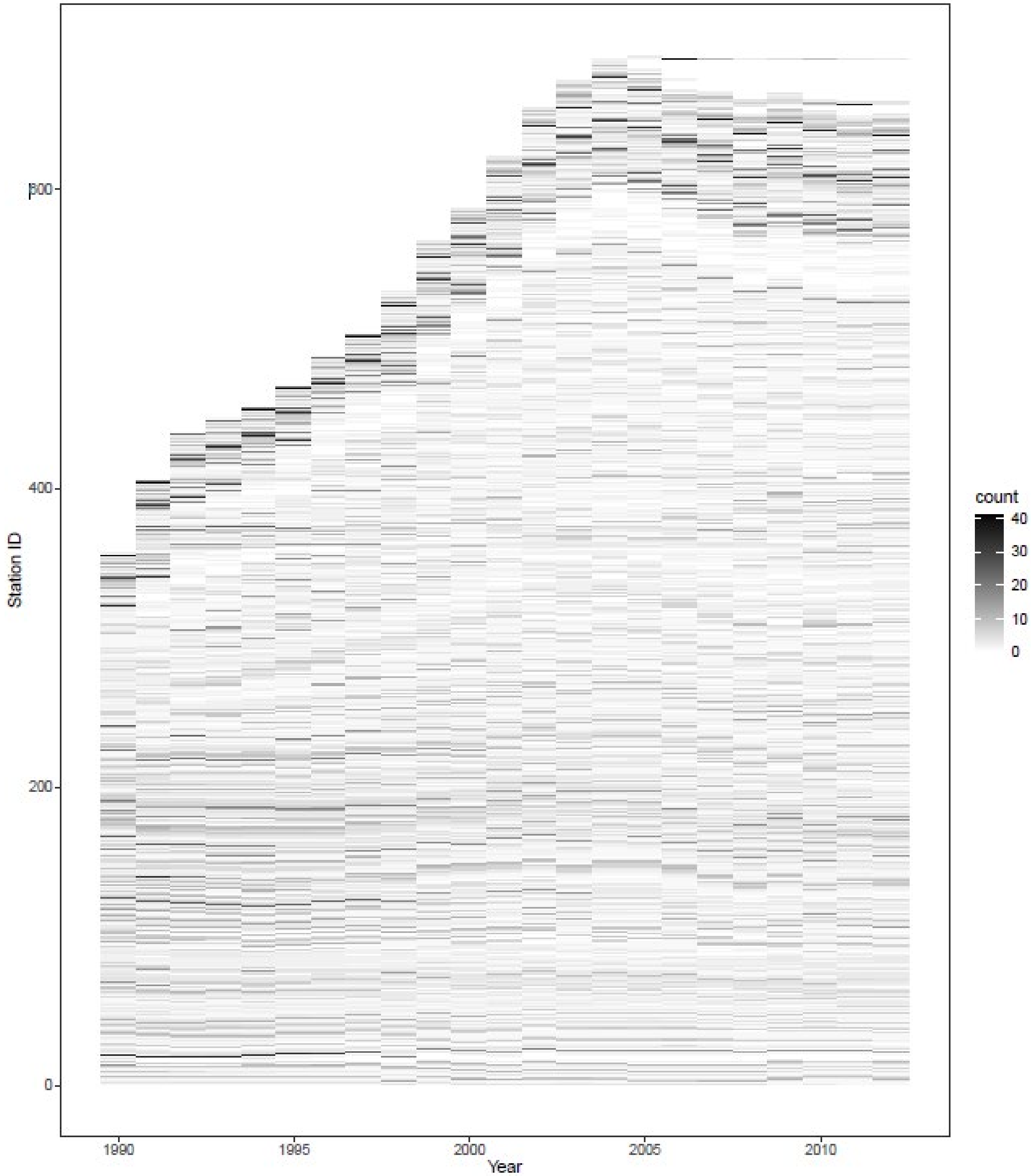
Note: All values are in percentage. Distances refer to the distance of a weather station from the centroid of a ZIP code tabulation area to which the station was matched.

FIGURE A1. SPATIAL CORRELATION IN ZIP CODE TABULATION AREA TEMPERATURES



Note: The key shows different ranges of daily mean temperatures. The figure shades ZCTAs according to their value of daily mean temperatures, averaged over the sample period.

FIGURE A2. A VISUALIZATION OF ZCTA MATCHES BY STATION-YEAR



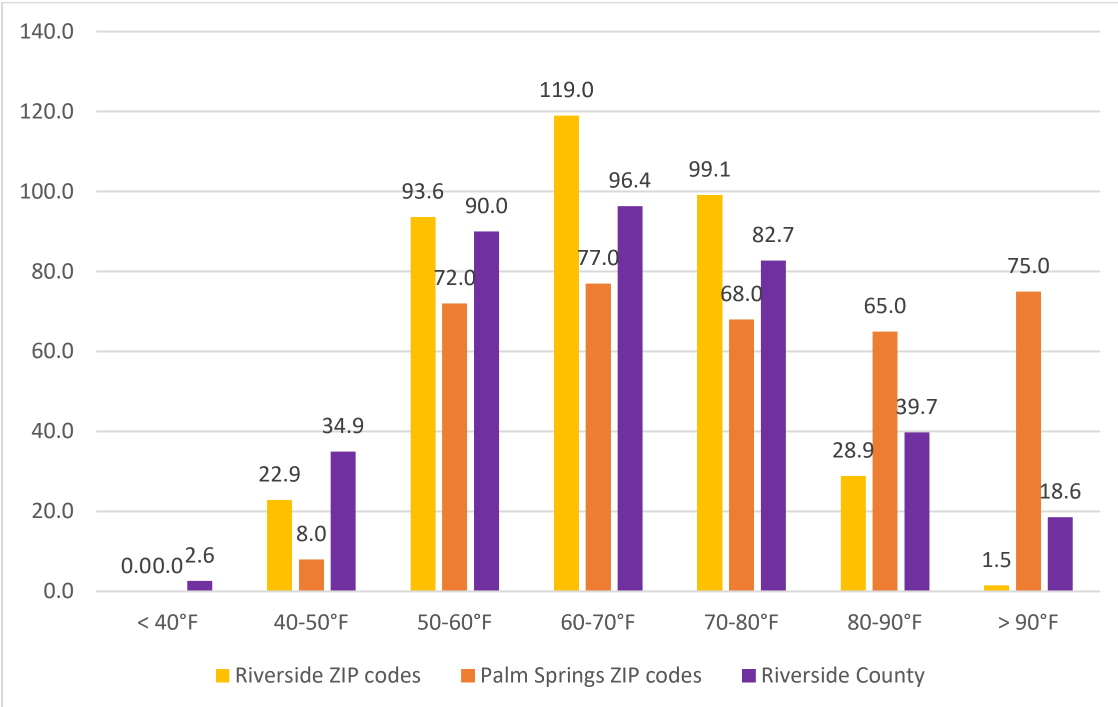
<u>Note</u>: The key shows the number of ZCTAs matched to a weather station if it was operating in a given year. The figure illustrates the number of matches for a given station in a given year as a horizontal bar. The darker the bar's shade, the greater the number of ZCTA matches represented. The figure also illustrates how the number of weather stations in California has increased over time.

TABLE A2. SPATIAL CORRELATION IN TEMPERATURES AND THE EVOLVING SET OF WEATHER STATIONS

Panel:	**A. Baseline Estimate**			**B. Constraining matches to ≤ 20**			**C. Using stations from 1991**		
Dependent Variable:	**Birth weight (grams)**			**Birth weight (grams)**			**Birth weight (grams)**		
	Trimester 1	Trimester 2	Trimester 3	Trimester 1	Trimester 2	Trimester 3	Trimester 1	Trimester 2	Trimester 3
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Below 40°F	-0.10	0.05	0.15*	-0.03	0.10	0.23**	-0.03	0.07	0.19*
	(0.06)	(0.06)	(0.07)	(0.08)	(0.06)	(0.08)	(0.07)	(0.06)	(0.07)
40-50°F	0.04	-0.10**	-0.07*	0.04	-0.10**	-0.09**	0.06*	-0.07*	-0.03
	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
60-70°F	0.13**	-0.20**	-0.07**	0.13**	-0.20**	-0.11**	0.16**	-0.17**	-0.01
	(0.02)	(0.02)	(0.02)	(0.03)	(0.03)	(0.02)	(0.02)	(0.02)	(0.02)
70-80°F	0.22**	-0.28**	-0.15**	0.21**	-0.27**	-0.22**	0.28**	-0.25**	-0.06*
	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
80-90°F	0.13**	-0.36**	-0.28**	0.05	-0.40**	-0.36**	0.18**	-0.31**	-0.21**
	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)	(0.05)	(0.04)	(0.04)	(0.04)
Above 90°F	0.23**	-0.14*	0.00	0.18*	-0.18*	-0.13	0.30**	-0.10	0.07
	(0.08)	(0.07)	(0.08)	(0.08)	(0.07)	(0.09)	(0.07)	(0.07)	(0.08)
Observations:		10,970,246			8,760,806			10,970,246	

Note: Cells report estimates of the temperature impact by bin and trimester. Standard errors, clustered at ZIP codes, are shown in parentheses. ** p<1%. * p<5%. Throughout, the dependent variable is infant birth weight (in grams). Panel A reproduces the baseline birth weight results. Panels B and C present birth weight results with corrections for spatial dependence in temperatures and for the changing set of weather stations over time, respectively. In panel B, the sample sheds a fifth of observations as it drops ZCTAs if they were one of more than twenty matched to a weather station in a given year. This restriction is imposed to reduce spatial dependence in temperatures stemming from too many ZCTAs sharing the same station-level temperature data. In panel C, the set of weather stations matched to ZCTAs on a nearest-neighbor basis is held constant, i.e. only the 413 stations from the year, 1991, are used to build infant-specific thermal exposures. Each regression includes fixed effects for the location of birth (i.e. ZIP code fixed effects), the timing of birth, type of birth, the infant's sex and race, each parent's age-group and schooling attainment, as well as indicators for health insurance coverage and prenatal care usage. Fixed effects for the timing of birth refer to the day of the week, month and year of birth. Fixed effects for the type of birth indicate if a birth was singleton, twin, triplet, quadruplet, quintuplet or more. Controls for health insurance are indicators for Medicaid/self-paying/other insurance; the omitted category is private insurance. Controls for prenatal care are indicators for the pregnancy month when the mother first sought care.

FIGURE A3. TEMPERATURE DISTRIBUTIONS: ZIP CODE AREAS V. COUNTY



Note: Data is from 2011. Compare the distribution of daily mean temperatures for Riverside county against the distribution for Riverside ZIP code areas and for Palm Springs ZIP code areas. Clearly, the county distribution is not representative of either city's temperatures; it greatly exaggerates the number of extreme cold and extreme heat days in Riverside ZIP codes while vastly underrepresenting the number of extreme heat days in Palm Springs.

TABLE A3. CHOICE OF THIRD TRIMESTER LENGTH

Panel:	A. Imputed a 91-day third trimester			B. Imputed 60-day third trimester		
Dependent Variable:	Birth weight (grams)			Birth weight (grams)		
	Trimester 1	Trimester 2	Trimester 3	Trimester 1	Trimester 2	Trimester 3
	(1)	(2)	(3)	(4)	(5)	(6)
Below 40°F	-0.10	0.05	0.15*	-0.05	0.08	0.35**
	(0.06)	(0.06)	(0.07)	(0.06)	(0.06)	(0.09)
40-50°F	0.04	-0.10**	-0.07*	0.06*	-0.07*	0.00
	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.04)
60-70°F	0.13**	-0.20**	-0.07**	0.13**	-0.20**	-0.04
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.03)
70-80°F	0.22**	-0.28**	-0.15**	0.24**	-0.30**	-0.14**
	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.04)
80-90°F	0.13**	-0.36**	-0.28**	0.15**	-0.37**	-0.28**
	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)	(0.05)
Above 90°F	0.23**	-0.14*	0.00	0.29**	-0.15	0.08
	(0.08)	(0.07)	(0.08)	(0.07)	(0.07)	(0.12)
Observations:	10,970,246			10,970,246		

Note: Cells report estimates of the temperature impact by bin and trimester. Standard errors, clustered at ZIP codes, are shown in parentheses. ** p<1%. * p<5%. Throughout, the dependent variable is infant birth weight (in grams). Panel A reproduces the baseline birth weight results where all observations in the sample were imputed a third trimester of 91 days. Panel B presents birth weight results with all observations assigned third trimester exposure as if it were exactly 60 days long. Each regression includes fixed effects for the location of birth (i.e. ZIP code fixed effects), the timing of birth, type of birth, the infant's sex and race, each parent's age-group and schooling attainment, as well as indicators for health insurance coverage and prenatal care usage. Fixed effects for the timing of birth refer to the day of the week, month and year of birth. Fixed effects for the type of birth indicate if a birth was singleton, twin, triplet, quadruplet, quintuplet or more. Controls for health insurance are indicators for Medicaid/self-paying/other insurance; the omitted category is private insurance. Controls for prenatal care are indicators for the pregnancy month when the mother first sought care.

TABLE A4. THE IMPACT OF TEMPERATURE ON FETAL DEATH BY SEASON OF CONCEPTION

Dependent Variable:	**Foetal death**											
Conceived during:	Sep/Oct/Nov			Dec/Jan/Feb			March/Apr/May			June/July/Aug		
Coincides with:		Winter		Winter		Summer		Summer		Summer		Winter
	Trimester1	Trimester2	Trimester3	Trimester1	Trimester2	Trimester3	Trimester1	Trimester2	Trimester3	Trimester1	Trimester2	Trimester3
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Below 40°F	0.000007	0.000065**	-0.000165**	0.000058**	0.000016	0.000146	-0.000049	0.000181*	-0.000068**	0.000281**	0.000023	-0.000095**
	(0.000013)	(0.000014)	(0.000030)	(0.000018)	(0.000039)	(0.000090)	(0.000040)	(0.000075)	(0.000014)	(0.000060)	(0.000015)	(0.000014)
40-50°F	0.000039**	0.000033**	-0.000053**	0.000015*	0.000009	-0.000103**	0.000012	0.000131**	-0.000010	0.000156**	0.000028**	-0.000024**
	(0.000006)	(0.000005)	(0.000017)	(0.000006)	(0.000018)	(0.000031)	(0.000017)	(0.000031)	(0.000006)	(0.000027)	(0.000007)	(0.000006)
60-70°F	-0.000181**	0.000072**	0.000141**	0.000078**	0.000220**	-0.000069**	0.000107**	-0.000065**	-0.000170**	-0.000068**	-0.000230**	0.000096**
	(0.000007)	(0.000006)	(0.000006)	(0.000005)	(0.000007)	(0.000010)	(0.000005)	(0.000008)	(0.000006)	(0.000012)	(0.000007)	(0.000006)
70-80°F	-0.000267**	0.000152**	0.000198**	0.000200**	0.000328**	-0.000146**	0.000172**	-0.000088**	-0.000246**	-0.000086**	-0.000329**	0.000104**
	(0.000009)	(0.000012)	(0.000008)	(0.000013)	(0.000009)	(0.000011)	(0.000007)	(0.000009)	(0.000008)	(0.000012)	(0.000010)	(0.000011)
80-90°F	-0.000260**	0.000238**	0.000180**	0.000325**	0.000262**	-0.000133**	0.000159**	-0.000076**	-0.000296**	-0.000043**	-0.000361**	0.000162**
	(0.000022)	(0.000040)	(0.000010)	(0.000047)	(0.000011)	(0.000011)	(0.000009)	(0.000011)	(0.000019)	(0.000013)	(0.000020)	(0.000045)
Above 90°F	-0.000446**	0.000982	0.000141**	0.000390	0.000310**	-0.000188**	0.000238**	-0.000031	-0.000334**	0.000050**	-0.000482**	0.000713**
	(0.000084)	(0.000503)	(0.000017)	(0.000426)	(0.000020)	(0.000021)	(0.000022)	(0.000021)	(0.000069)	(0.000019)	(0.000099)	(0.000246)
Observations		2,805,224			2,778,519			2,691,747			2,694,756	

Note: Cells report estimates of the temperature impact on fetal death (a binary outcome) by bin and trimester. Standard errors, clustered at ZIP codes, are shown in parentheses. ** p<1%. * p<5%. Control variables include fixed effects for the location of birth (i.e. ZIP code fixed effects), the timing of birth, type of birth, the infant's sex and race, each parent's age-group and schooling attainment, as well as indicators for health insurance coverage and prenatal care usage. Fixed effects for the timing of birth refer to the day of the week, month and year of birth. Fixed effects for the type of birth indicate if a birth was singleton, twin, triplet, quadruplet, quintuplet or more. Controls for health insurance are indicators for Medicaid/self-paying/other insurance; the omitted category is private insurance. Controls for prenatal care are indicators for the pregnancy month when the mother first sought care.

TABLE A5. MECHANISMS UNDERLYING THE TEMPERATURE IMPACT ON BIRTH WEIGHT

Panel:	**A. Neither parent attended college**			**B. At least one parent attended college**		
Dependent Variable:	**Birth weight (grams)**			**Birth weight (grams)**		
	Trimester 1	Trimester 2	Trimester 3	Trimester 1	Trimester 2	Trimester 3
Below 40°F	-0.11	-0.02	0.08	-0.10	0.11	0.18
	(0.10)	(0.09)	(0.10)	(0.09)	(0.08)	(0.09)
40-50°F	0.03	-0.16**	-0.04	0.04	-0.07*	-0.09*
	(0.05)	(0.04)	(0.04)	(0.04)	(0.03)	(0.04)
60-70°F	0.13**	-0.23**	-0.02	0.13**	-0.17**	-0.11**
	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
70-80°F	0.20**	-0.33**	-0.13**	0.22**	-0.24**	-0.17**
	(0.05)	(0.04)	(0.05)	(0.04)	(0.04)	(0.04)
80-90°F	0.15*	-0.36**	-0.18**	0.10	-0.38**	-0.37**
	(0.06)	(0.06)	(0.06)	(0.05)	(0.05)	(0.05)
Above 90°F	0.35**	-0.21*	0.15	0.04	-0.11	-0.20*
	(0.11)	(0.09)	(0.12)	(0.12)	(0.09)	(0.10)
Observations:		4,902,039			6,068,207	

Note: Cells report estimates of the temperature impact on birth weight by bin and trimester. Standard errors, clustered at ZIP codes, are shown in parentheses. ** p<1%. * p<5%. Panel A shows the birth weight regression where neither parent attended college. Panel B shows the birth weight regression where at least one parent attended college. Control variables in both regressions include fixed effects for the location of birth (i.e. ZIP code fixed effects), the timing of birth, type of birth, the infant's sex and race, each parent's age-group and schooling attainment, as well as indicators for health insurance coverage and prenatal care usage. Fixed effects for the timing of birth refer to the day of the week, month and year of birth. Fixed effects for the type of birth indicate if a birth was singleton, twin, triplet, quadruplet, quintuplet or more. Controls for health insurance are indicators for Medicaid/self-paying/other insurance; the omitted category is private insurance. Controls for prenatal care are indicators for the pregnancy month when the mother first sought care.