In Utero Heat Exposure and Infant Health in Brazil

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July 31, 2024

Abstract

This study quantifies the cumulative effects of in-utero heat exposure on infant health outcomes in Brazil. We merge temperature data from weather stations with rich administrative microdata on live births and stillbirths registered in Brazil between 2005 and 2018. We find a negative and significant effect of heat waves on birth weight and the probability of full-term pregnancy for live births, indicating that heat waves induce earlier births. We further document significant gradients in these detrimental effects of extreme weather on neonatal health by maternal education, race, and age, and by municipality-level availability of primary care units aimed at providing care for mothers during pregnancy and at childbirth. We also observe a significant increase in stillbirths following a heat wave.

Keywords:
Heat waves, Infant health outcomes, Stillbirths, Brazil, Climate change.

JEL classification:
I12, J13, Q54

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Acknowledgements: We thank Natália Trigo for excellent research assistance. Financial support is gratefully acknowledged from the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.

1 Introduction

Recent studies have shown that the interval between extreme weather events has been decreasing, and their intensity has become less predictable (Cai et al., 2014; Kovats et al., 2003). It has been well documented that these events have adverse effects on health and educational outcomes in multiple ways and, more importantly, that these effects can persist for years (Maccini and Yang, 2009). Especially in the case of infants, these effects can materialize only years later (Karbownik and Wray, 2019). It is, therefore, crucial to understand the effects of extreme weather not only on human health in general, but also on neonatal health (Currie and Rossin-Slater, 2013).

According to Rosales-Rueda (2018), infants affected by the "El Niño" floods in Ecuador in 1997 and 1998, both in utero and during their first year of life, experience negative impacts on health and educational outcomes. These consequences may not be apparent immediately but may materialize and persist over time. Existing evidence has shown that exposure to extreme heat during pregnancy can increase infant mortality and stillbirths (Banerjee and Maharaj, 2020) as well as preterm births (McElroy et al., 2022), and maternal emergency hospitalization (Kim et al., 2021). Importantly, the evidence also suggests a negative relationship between extreme heat and birth weight, which can vary depending on the timing of exposure during pregnancy (Deschênes et al., 2009).

While most of existing evidence has focused on the effect of in utero exposure to extreme heat on infant mortality and birth weight, relatively less is known of other neonatal outcomes that also serve as valuable health indicators, including APGAR scores and the incidence of anomalies experienced at birth (including congenital cardiovascular and respiratory conditions). On one hand, APGAR scores provide immediate measures of the health of the newborn in the first minutes of life. On the other hand, anomalies experienced at birth capture health conditions that can have a more long-lasting effect on a newborn's quality of life. More importantly, while there is substantial evidence on the effect of extreme heat on infant mortality within a developing country setting, the evidence on birth weight and other neonatal health measures and the extent to which the potential effects could be unequally distributed among the most vulnerable communities remains relatively scant. Addressing this gap could provide potentially valuable policy implications in the design of adaptation and mitigation strategies tailored to serve the communities more severely affected by extreme weather.

In this study, we investigate how in utero exposure to heat waves affect infant health outcomes in Brazil, a large developing country characterized by significant income inequality and disparities in access to health care. We merge temperature data obtained from weather stations with rich microdata containing information on all live births and stillbirths registered in the country. We use daily maximum temperatures measures, and a version of temperature measures that are adjusted for humidity. Humidity exacerbates heat stress by rendering sweating, the body's natural cooling mechanism, ineffective. We compare these temperature measures with historical average summer temperatures to detect exposure to excessive heat.

We conduct analyses at the individual level and at the level of municipalities. Our results indicate that exposure to excessive heat negatively affects birth weight and increases the incidence of preterm births. Furthermore, exposure to excessive heat (over the last 7, 30, 60, and 90 days) is associated with an increase in stillbirths. At the individual level, we find that heat exposure negatively affects birth weight, increases the incidence of preterm births, and raises the probability of the baby being born with an anomaly. We do not find significant effects on APGAR scores, which measure the health of a newborn in the first minute and after the first five minutes of life.

Our analysis contributes to the literature by quantifying the heterogeneity of in utero heat exposure at different stages of the last trimester of gestation, indicating stronger effects when heat exposure occurs in the last month. Taking full advantage of our rich microdata, we also document differences in these effects by maternal characteristics. Similarly, leveraging the Brazilian context, we explore a further rich sources of heterogeneity in the form of municipality-level differences in the (i) coverage of social assistanc programs, and (ii) availability of primary care units focused on family health, which has been experiencing expansions over the past two decades.[1]

Our heterogeneity results indicate that most of the negative effects of in utero heat exposure on birth weight are concentrated among mothers from relatively more disadvantaged socioeconomic groups. That is, the losses on birth weight are higher among mothers with lower education and from minority racial groups. Similarly, these losses are concentrated among mothers that are more vulnerable from a physiological standpoint as the decrease in birth weight is relatively higher among older mothers. Similarly, our heterogeneity checks also indicate that most of the detrimental effects of in utero heat exposure on neonatal health (especially on birth weight and anomalies at birth) are concentrated in areas with lower availability of these local primary family health units. Such heterogeneity provides suggestive evidence that the availability of these primary care units help mitigate the adverse effects of extreme temperature on neonatal health.

The paper is organized as follows, besides this introduction. Section 2 briefly describes the dataset. In the third section, we present the identification strategy for the empirical analysis. Next, we describe the main results. Finally, in Section 5 we conclude.

2 Data

We merge rich microdata containing information on all live births registered in Brazil between 2005 and 2018 with information on extreme heat by municipality obtained from weather stations. In this section, we provide further details from

[1]During the mid-1990s, the Brazilian Unified Health System (Sistema Unico de Saude), established the Family Health Program (Programa Saude de Familia) which has been steadily growing as more municipalities have been joining the program since the early 2000s. The goal of the program has been focused on shifting the provision of healthcare associated with Family and Community Medicine away from hospital-based care and towards a teams-based model consisting of doctors, nurses, and community health centers provided by local goverments. For more information, refer to (Rocha and Soares, 2010).

the different data sources we use in our empirical analysis.

Live Births. We obtain information on the characteristics of all live births registered in Brazil during our sample period from the Sistema de Informações sobre Nascidos Vivos (SINASC). SINASC data are provided by the Ministry of Health through the digitization of Declarações de Nascido Vivo (DN), which are filled out by health practitioners or midwives who assist in the birth or care of a newborn. From these data, we obtain birth-specific information, such as birth weight, 1 and 5-minute APGAR scores, type of delivery (c-section or vaginal), number of pre-natal care visits, number of gestation weeks, gender and race of the newborn, and indicators for any form of anomaly, such as congenital conditions (more than 90% of anomalies documented correspond to congenital conditions, such as congenital heart or neurological problems and to chromosomal abnormalities, such as Down syndrome). We also have information on mothers' sociodemographic characteristics such as age, education, and occupation. Table 1 provides descriptive statistics of live births registered during our period of analysis.

Stillbirths. We obtain information on the characteristics of stillbirths registered in Brazil during our sample period from the Sistema de Informação sobre Mortalidade Declaração de Óbitos Fetais (System of Stillbirth Mortality). These data are provided by the Oswaldo Cruz Foundation.[2] From these data, we obtain stillbirth-specific information, such as stillbirth weight, number of gestation weeks, type of delivery, and gender of the newborn. We also have information on mothers' sociodemographic characteristics, including age and education. Table 2 provides descriptive statistics of stillbirths registered during our period of analysis.

Primary Health Care Coverage. We obtain information on the coverage of primary care units at the municipal level from 2007-2018. Table 3 presents descrip-

[2] https://pcdas.icict.fiocruz.br/conjunto-de-dados/sistema-de-informacao-sobre-mortalidade-declaracao-de-obitos-fetais-sim-dofet/

Table 1: Descriptive Statistics of Live Births Registered between 2005-2018

		Regions				
	Overall	North	Northeast	Southeast	South	Central-West
Mother's Characteristics:						
Age	25.862	24.235	25.129	26.656	26.560	25.677
Completed High School	0.171	0.115	0.119	0.200	0.214	0.217
Married	0.342	0.204	0.290	0.404	0.373	0.353
Cohabiting	0.137	0.244	0.167	0.082	0.142	0.147
Single	0.521	0.552	0.542	0.514	0.485	0.500
Previous Miscarriage	0.149	0.182	0.172	0.133	0.122	0.160
Number of Prev. Kids	1.095	1.529	1.244	0.950	0.933	1.038
Birth Characteristics:						
Birth at Hospital	0.980	0.936	0.972	0.992	0.994	0.990
7 or More Prenatal Visits	0.622	0.399	0.494	0.729	0.750	0.656
Cesarean Birth	0.523	0.419	0.444	0.577	0.582	0.584
Birth Weight (in grams)	3,183	3,214	3,220	3,149	3,179	3,179
APGAR Score, 1 Min.	8.269	8.182	8.165	8.326	8.347	8.332
APGAR Score, 5 Min.	9.313	9.266	9.214	9.353	9.382	9.406
Anomaly at Birth	0.008	0.005	0.007	0.009	0.008	0.007
Observations	40,995,572	4,400,744	11,920,240	16,056,786	5,376,758	3,241,044

Table 2: Descriptive Statistics of Stillbirths Registered between 2005-2018

		Regions				
	Overall	North	Northeast	Southeast	South	Central-West
Mother's Characteristics						
Age	27.05	25.79	26.80	27.52	28.21	26.93
Completed High School	0.14	0.11	0.12	0.16	0.18	0.18
Gender	0.52	0.53	0.52	0.52	0.53	0.53
Previous Miscarriage	0.54	0.46	0.60	0.48	0.67	0.54
Cesarean Birth	0.29	0.28	0.27	0.29	0.33	0.34
Lost occurred after 37 weeks	0.30	0.32	0.33	0.27	0.27	0.29
Stillbirth Causes:						
Placenta and Umbilical Cord Complications	0.18	0.18	0.19	0.15	0.24	0.23
Hipoxia	0.26	0.19	0.27	0.30	0.13	0.22
Maternal Cause	0.22	0.24	0.21	0.20	0.27	0.26
Observations	143,441	18,120	43,612	54,452	10,973	16,284

CID-10 used to generate stillbirth causes: 1) Maternal health causes: codes P00 P01 P03 and P04, 2) Maternal health causes by Placenta umbilical cord problems: codes P02, 3) Hipoxia: code P20 and 4) Other respiratory and cardiovascular conditions codes: P21 to P29.

tive statistics about the type of care and availability of health teams at a given municipality during our estimation time period. In further stages of this study, we intend to use geographic variation in primary health care variation over time to quantify the role of expansions to these services as a form of adaptation strategy available to the population, particularly those most susceptible to drastic changes in temperature.

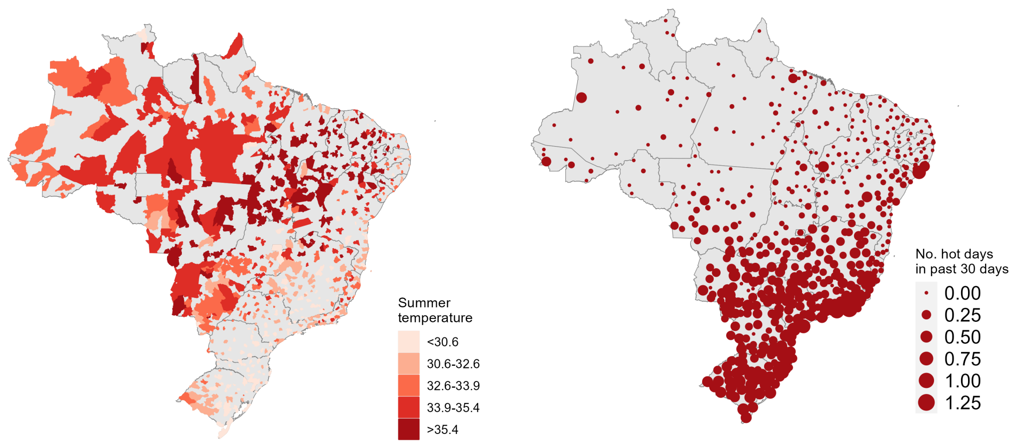
Table 3: Descriptive Statistics of Municipal Primary Care Units

		Regions				
	Overall	North	Northeast	Southeast	South	Central-West
Number of Saude Familia Teams	5.997	5.891	7.343	6.314	3.931	5.046
Number of Atencao Basica Teams	7.604	7.103	7.886	9.381	5.307	6.506
Pop. Share Covered by Saude Familia	82.043	76.324	92.230	73.334	78.985	87.312
Pop. Share Covered by Atencao Basica	86.646	78.078	92.952	82.155	85.573	89.444
Observations	567,744	458,22	18,2970	170,136	121,260	47,556

Temperature. Measurements of extreme heat on the municipality-level are constructed using information from weather stations, operated in 576 municipalities by the Instituto Nacional de Meteorologia (INMET).[3] The stations provide daily records of temperature, relative humidity, and precipitation in our study period from 2005 to 2018. To calculate the typical summer temperature in each municipality, we average the daily maximum temperature within each year-month, then select the hottest month in each year, and average across all years observed. This yields a location-specific measure of typical summer heat, which a population might be reasonably adapted to. We define a "hot day" as a day in excess of 4.5C above the typical summer temperature. To measure cumulative exposure to excessive heat, we calculate the total number of hot days in the past 30, 60, and 90 days. Analogously, we calculate typical summer heat and the number of excessively hot days using humidity-adjusted measures of temperature, dubbed

[3] `https://portal.inmet.gov.br/`

Figure 1: Spatial Distribution of Typical Summer Temperatures and the Average Number of Excessively Hot Days in the Past 30 Days Relative to the Typical Summer Temperature



(a) Average summer temperatures **(b) Average number of excessively hot days within past 30 days**

"wet bulb temperature".[4] As alternative measures, we calculate the moving sum of days above 32 degrees Celsius in the past 30, 60, and 90 days, and the moving average temperature across the past 30, 60, and 90 days. Figure 1 shows the average summer temperature per municipality in Panel (a) and the average number of excessively hot days in the past 30 days, relative to the municipality-specific summer temperature in Panel (b). Table 4 presents summary statistics. On any given day, the average number of unusually hot days in the past 30 days is 0.136 across municipality-days. The average summer temperature across municipalities is 32.8 C.

[4]https://physicscalc.com/physics/wet-bulb-calculator/

Table 4: Descriptive Statistics of Temperature

	Mean	SD	95th Perc
Number of hot days in last 30 days	0.136	0.774	1.000
Number of hot days in last 60 days	0.271	1.244	2.000
Number of hot days in last 90 days	0.406	1.609	3.000
Number of wet-bulb hot days in last 30 days	0.117	0.598	1.000
Number of wet-bulb hot days in last 60 days	0.233	1.017	1.000
Number of wet-bulb hot days in last 90 days	0.348	1.366	2.000
Daily max temperature (C)	29.5	4.9	36.2
Daily max temperature, humidity-adjusted	23.4	3.9	28.7
Typical summer temperature across municipalities (C)	32.8	3.0	37.1

NOTES: One observation is a municipality-day. Hot days are defined as exceeding the municipality-specific typical summer temperature by at least 4.5C. "Wet-bulb" temperatures are adjusted for humidity.

3 Empirical Strategy

To capture the effects of exposure to hot days during the last trimester of gestation, we start by implementing the following specifications on our sample of individual live births registered between 2005 and 2018:

$$B_{i,t} = \alpha + \beta Hot\_days^{m} + \gamma \mathbf{X}_{it} + \eta_{qt} + \epsilon_{it} \quad \text{where } m = \{1, 2, 3\} \tag{1}$$

where $B_{i,t}$ denotes the birth outcome of interest from women i's pregnancy occurring in year t, $\mathbf{X}_{it}$ denotes a vector of controls relating women i's sociodemographic characteristics captured at the time of birth, and η_{qt} captures year-quarter of birth fixed effects to account for potential seasonality. Importantly, Hot_days^{m} captures the number of days during the last m months of gestation that a pregnant woman was exposed to heat by taking into consideration the average temperature in a given municipality. By defining hot days relative to municipality-specific historical averages, we implicitly control for municipality-level climate differences, thus allowing us to identify the causal effect of significant deviations from these municipality-specific standards.

Within this specification, β is our parameter of interest as it captures the effect of experiencing one additional hot day during the last m months of pregnancy. Notably, we compute heterogeneous effects of *in utero* exposure to heat by the number of months before birth, focusing within the last trimester of gestation.

4 Results

We begin by presenting the overall effects of exposure to hot days in the last three, two, and one months of pregnancy on birth weight, the incidence of premature births, APGAR scores, and the incidence of anomalies at birth. We then proceed to explore the extent to which the overall effects are heterogeneously distributed across municipalities based on the availability of primary care units focused on family health.

4.1 Main Results

We observe in Table (5) that one additional hot day in the last month of gestation reduces birth weight by 4.15 grams and increases the probability of a preterm birth by .16 percentage points. We do not observe significant impacts on Apgar scores. Comparing panels (A) and (B) shows that the estimates are similar when adjusting for humidity. When we account for humidity in measuring excessively hot days, we also find a significant increase in the probability of an anomaly at birth by .04 percentage points. We validate the results obtained using the individual-level microdata by obtaining similar results at the municipality level for the highest temperature and the humidity-adjusted heat as in Tables (6) and (7). Tables 8 and 9 show the effects of excessively hot days during the last 2 months and the last 3 months of gestation. The estimates decrease slightly in magnitude, suggesting that excessive heat is more detrimental in the final month of gestation.

Our findings suggest that increased exposure to hot days during the last term of pregnancy has considerable negative effects on newborns' birth weight and increases the incidence of preterm births. Moreover, by documenting heterogeneous effects across the months during the last term in which mothers are exposed to heat, we can pinpoint that exposure to hot days in the last month of gestation has the most detrimental effect on newborns' birth weight. When adjusting our measure of heat to account for humidity (our wetbulb hot day's measure), we find similar results on birth weight compared to the ones obtained when using the unadjusted measure.

Importantly, upon adjusting for humidity, we find that exposure to wetbulb hot days increases the likelihood that a child is born with an anomaly by .3 and .4 per 1,000 births, with the bigger effect documented when exposure to wetbulb hot days occurs during the month prior to birth. Considering that, on average, approximately 8 out of 1,000 newborns experience an anomaly at birth, our point estimates suggest an increase in the incidence of these anomalies of approximately 3% and 5%.

Furthermore, when using our data on stillbirths at the municipality level, we find that heat waves (lagged by 7, 30, 60, and 90 days) are linked to a rise in stillbirths as in Table (10). Our results are in line with Deschênes et al. (2009), where exposure to hot days is associated with a statistically significant decline in birth weight.

Our results are consistent with the existing literature on heat waves and birth and stillbirth outcomes. The increase in stillbirths that we observe aligns with Banerjee and Maharaj (2020), who finds that exposure to extreme heat during pregnancy can result in outcomes such as infant mortality. Similarly, McElroy et al. (2022) identifies negative effects on stillbirths and preterm births, noting that an increase in heat waves raises the incidence of both outcomes.

Table 5: Effects of Exposure to Heat During the Last Month of Pregnancy on Birth Outcomes (at the individual level)

	(1) Birth Weight	(2) Premature Birth	(3) Apgar Score 1 Min.	(4) Apgar Score 5 Min.	(5) Anomaly at Birth
	(A) No Humidity Adjustment				
Number of Hot Days, Past 30 Days	-4.1514***	0.0016***	-0.0010	-0.0082	0.0001
	(0.681)	(0.000)	(0.002)	(0.005)	(0.000)
Constant	3157.4621***	0.0821***	8.0045***	9.1348***	0.0051***
	(9.622)	(0.006)	(0.035)	(0.045)	(0.001)
Observations	10,117,506	10,119,218	9,950,188	9,955,953	9,934,394
	(B) Humidity-Adjusted Heat Measure				
Wetbulb Hot Days, Past 30 Days	-4.1512***	0.0010*	0.0032	0.0103	0.0004*
	(1.394)	(0.001)	(0.003)	(0.007)	(0.000)
Constant	3157.1940***	0.0825***	8.0020***	9.1234***	0.0050***
	(9.791)	(0.006)	(0.035)	(0.047)	(0.001)
Observations	10,117,506	10,119,218	9,950,188	9,955,953	9,934,394

Notes: Standard errors are clustered at the level of the municipality of birth. Controls included correspond to maternal characteristics such as age, education, marital status, number of children, and previous miscarriages. Further controls include the child's gender and race. Statistical significance is indicated as such: *** 99%, ** 95%, * 90%. Year-Quarter of birth fixed effects are included in the estimation.

Table 6: Average Daily Tmax/humidity on birth 2005-2018

	(1) Ln births by 100.000 inhab	(2) Ln Weight at Birth	(3) Full-Term Pregnancy
Average Daily Tmax/humidity Past 30	0.007***	-0.05***	0.0000
	(0.001)	(0.013)	(0.000)
Observations	1,269,396	1,269,396	1,269,396

Standard errors in parentheses

The dependent variables are: 1) Ln birth per 100,000 inhabitants, 2) Ln weight on births, and 3) births that occurred when pregnancy was full term (more than 37 weeks). The average daily wetbulb is the highest temperature controlled by humidity in the last 30 days. All columns display OLS estimates with controls (mean years of schooling and mean age) and FEs (municipality, quarter, and daily fixed effects). All regressions are weighted by the total population in the municipality. Standard errors (in parentheses) are clustered by municipalities.

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

Table 7: Average Daily Tmax on birth 2005-2018

	Ln births by 100.000 inhab	Ln Weight at Birth	Full-Term Pregnancy
Average Daily Tmax Past 30	0.005***	-0.03**	0.0002*
	(0.001)	(0.014)	(0.000)
Observations	1,269,396	1,268,983	1,269,396

Standard errors in parentheses

The dependent variables are: 1) Ln birth per 100,000 inhabitants, 2) Ln weight on births, and 3) births that occurred when pregnancy was full term (more than 37 weeks). The average daily wetbulb is the highest temperature controlled by humidity in the last 30 days. All columns display OLS estimates with controls (mean years of schooling and mean age) and FEs (municipality, quarter, and daily fixed effects). All regressions are weighted by the total population in the municipality. Standard errors (in parentheses) are clustered by municipalities.

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

Table 8: Effects of Exposure to Heat During the Last Two Months of Pregnancy on Birth Outcomes (at the individual level)

	(1) Birth Weight	(2) Premature Birth	(3) Apgar Score 1 Min.	(4) Apgar Score 5 Min.	(5) Anomaly at Birth
(A) No Humidity Adjustment					
Number of Hot Days, Past 60 Days	-3.5394***	0.0011***	-0.0003	-0.0070	0.0001
	(0.601)	(0.000)	(0.002)	(0.004)	(0.000)
Constant	3159.4277***	0.0817***	8.0043***	9.1389***	0.0051***
	(9.582)	(0.006)	(0.035)	(0.045)	(0.001)
Observations	10,070,988	10,072,659	9,905,584	9,911,347	9,888,891
(B) Humidity-Adjusted Heat Measure					
Wetbulb Hot Days, Past 60 Days	-3.2923***	0.0005	0.0031	0.0079	0.0003*
	(1.146)	(0.000)	(0.002)	(0.006)	(0.000)
Constant	3158.6552***	0.0825***	8.0002***	9.1200***	0.0049***
	(9.860)	(0.006)	(0.036)	(0.048)	(0.001)
Observations	10,070,988	10,072,659	9,905,584	9,911,347	9,888,891

Notes: Standard errors are clustered at the level of the municipality of birth. Controls included correspond to maternal characteristics such as age, education, marital status, number of children, and previous miscarriages. Further controls include the child's gender and race. Statistical significance is indicated as such: *** 99%, ** 95%, * 90%. Year-Quarter of birth fixed effects are included in the estimation.

Table 9: Effects of Exposure to Heat During the Last Three Months of Pregnancy on Birth Outcomes (at the individual level)

	(1) Birth Weight	(2) Premature Birth	(3) Apgar Score 1 Min.	(4) Apgar Score 5 Min.	(5) Anomaly at Birth
	(A) No Humidity Adjustment				
Number of Hot Days, Past 90 Days	-3.4148***	0.0009***	-0.0001	-0.0061	0.0001
	(0.553)	(0.000)	(0.002)	(0.004)	(0.000)
Constant	3160.2305***	0.0817***	8.0041***	9.1397***	0.0051***
	(9.564)	(0.006)	(0.036)	(0.045)	(0.001)
Observations	10,025,574	10,027,225	9,861,944	9,867,701	9,844,387
	(B) Humidity-Adjusted Heat Measure				
Wetbulb Hot Days, Past 90 Days	-2.9858***	0.0003	0.0026	0.0070	0.0003**
	(1.001)	(0.000)	(0.002)	(0.005)	(0.000)
Constant	3159.0305***	0.0829***	7.9999***	9.1189***	0.0048***
	(9.912)	(0.006)	(0.036)	(0.048)	(0.001)
Observations	10,025,574	10,027,225	9,861,944	9,867,701	9,844,387

NOTES: Standard errors are clustered at the level of the municipality of birth. Controls included correspond to maternal characteristics such as age, education, marital status, number of children, and previous miscarriages. Further controls include the child's gender and race. Statistical significance is indicated as such: *** 99%, ** 95%, * 90%. Year-Quarter of birth fixed effects are included in the estimation.

Table 10: Effects of Exposure to Heat on Stillbirth 2005-2018 (by municipality)

	(1) Ln Stillbirth	(2) Ln Stillbirth	(3) Ln Stillbirth	(4) Ln Stillbirth
Daily Tmax/humidity, Past 7 Days	0.0005***			
	(0.000)			
Daily Tmax/humidity, Past 30 Days		0.0007***		
		(0.000)		
Daily Tmax/humidity, Past 60 Days			0.0007***	
			(0.000)	
Daily Tmax/humidity, Past 90 Days				0.0007***
				(0.000)
Observations	71,358	71,358	71,358	71,358

Standard errors in parentheses

The dependent variable is Ln stillbirth per 100,000 inhabitants. Average daily Tmax/humidity is the mean of the highest temperature controlled by humidity. All columns display panel regressions with controls (mean years of schooling and mean age of the mothers, mean pregnancies that achieved 37 weeks or more, vaginal birth) and FEs (municipality and year fixed effects). All regressions are weighted by the total population in the municipality. Standard errors (in parentheses) are clustered by municipalities.

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

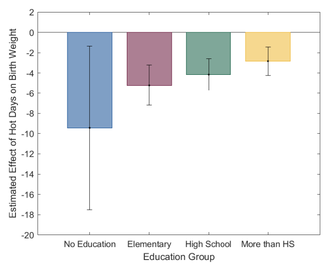
4.2 Heterogeneity

We now proceed to analyze the heterogeneity of the effects of heat exposure during the last month of pregnancy discussed above by primary care (focused on family medicine) coverage available at the municipality level and by maternal sociodemographic characteristics. For this analysis, we begin by partitioning observations into groups based on either maternal sociodemographic characteristics (including education, age, and race), and based on the number of family-oriented (saude familia) care teams available in the municipality in a given month. We then capture the heterogeneous effects of interest by estimating the specification described in (1) separately for each of the groups defined in each heterogeneity exercise. We described below the main takeways from this analysis.

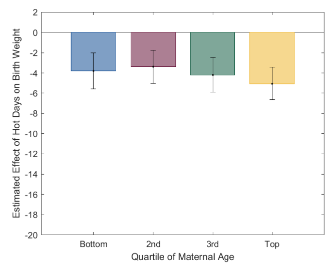
Maternal Sociodemographic Characteristics. Figure 2 presents the heterogeneity of the impact of in utero heat exposure during the last month of pregnancy on infant health outcomes by mothers' education, age, and race. The first row presents the estimated effect on the different sociodemographic groups on birth weight, the second row presents the results corresponding to the incidence of premature births, and the third row presents the resuls for the incidence of birth anomalies.

Our results indicate that the detrimental effects of in utero heat exposure on birth weight are much stronger among less-educated mothers, relatively older mothers, and mothers from non-white racial groups. To the extent that race and education are strongly correlated with income, the gradients documented across education and racial groups could shed some light on the extent to which the effects are concentrated among more economically disadvantaged groups. That is, these gradients would be consistent with more socioeconomically vulnerable women being more limited in their ability to adapt to extreme weather conditions during their pregnancy. For the incidence of anomalies at birth, we find no detectable significant heterogeneity across education, age, or racial groups.

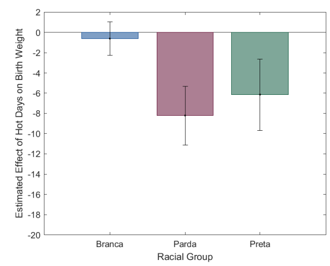
Figure 2: Heterogeneity in the Effect of Heat Exposure during Last Month of Pregnancy by Maternal Sociodemographic Characteristics



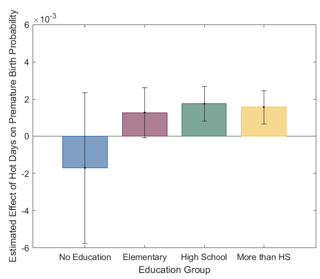
(a) Education



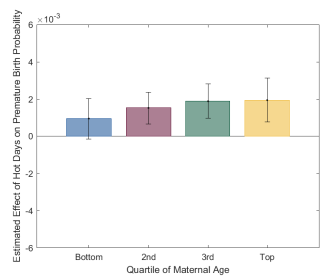
(b) Age



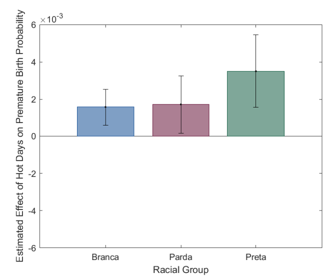
(c) Race



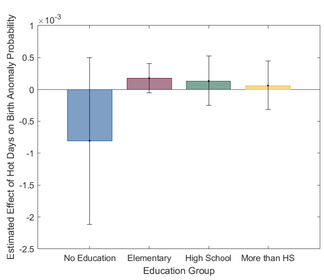
(a) Education



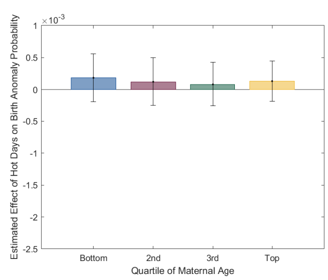
(b) Age



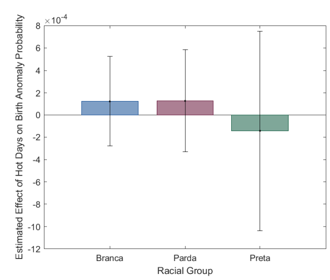
(c) Race



(a) Education



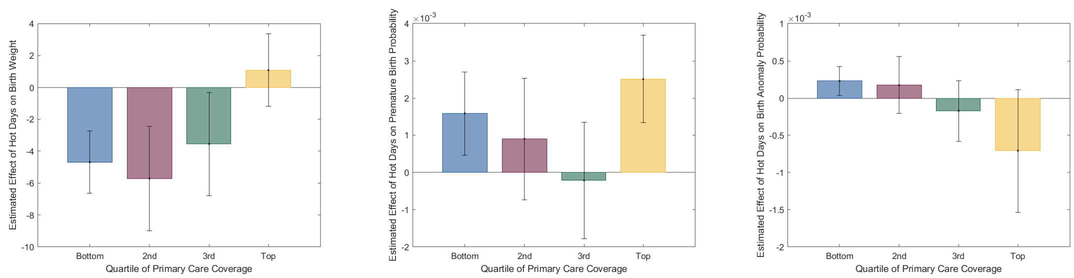
(b) Age



(c) Race

Maternal Health Care Availability and Prenatal Care Take Up. Figure 3 presents how the effect of exposure to hot days during the last month of pregnancy varies by the number of saude familia care teams available in mothers' municipality of residence.

Figure 3: Heterogeneity in the Effect of Heat Exposure during Last Month of Pregnancy by Quartile of Primary Care Teams Available at the Municipality of Residence

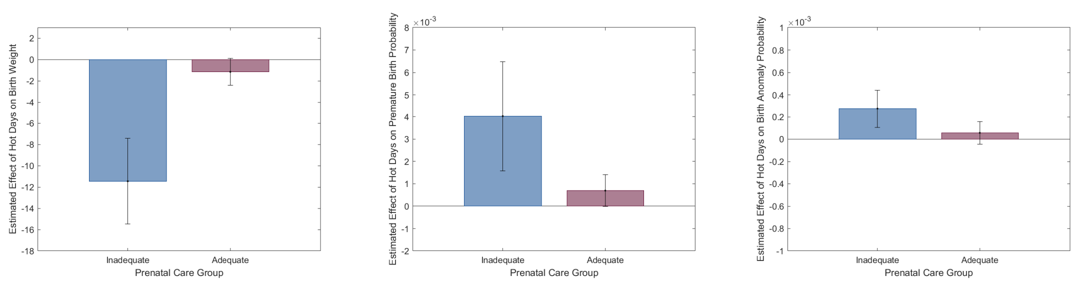


(a) Birth Weight **(b) Premature Birth** **(c) Anomaly at Birth**

For each of the figures presented in this section, the blue bar captures the effect of an additional hot day on the neonatal health outcome of interest in births occuring in municipalities at the bottom quintile of saude familia (SF) care teams availability. The burgundy and green bars capture the effect of exposure to an additional hot day on neonatal health outcomes in the second and third quartile of SF teams availability. Lastly, the yellow bar captures the corresponding effect on municipalities at the top quintile of the SF teams availability. For each of the bars, the bars in black capture the corresponding 95% confidence interval of our point estimates. The results show that most of the effects of in utero heat exposure on birth weight and the incidence of anomalies at birth are concentrated in municipalities at the bottom quartiles of SF care availability. These heterogeneous patterns are robust across the timing of exposure to heat during gestation. Notably, our results indicate that the increase in anomalies is predominantly focused at the bottom quartile of the SF care availability distribution, as this increase diminishes (and eventually vanishes) in the top quartiles, suggesting that the availability of these care units serve as a mitigating factor.

Interestingly, we find no significant heterogeneity in the effect of in utero heat exposure on premature births across the different quartiles of SF care availability as the point estimate is positive or statistically insignificant across quartiles. This provides interesting insights regarding the interpretation of our results on birth weight as part of the negative effects of heat exposure on birth weight could be attributed to the higher incidence of premature births. Nonetheless, we find that in municipalities in the quartiles where preterm births are not significantly affected by in utero heat exposure, birth weight is significantly decreased by exposure to heat during gestation. Similarly, while the incidence of premature births seems to increase in response to heat exposure in the top quartile, this does not translate into detrimental effects on birth weight. This could suggest that part of the negative effect of heat exposure during gestation on birth weight could be attributed to other pregnancy complications (such as maternal malnourishment or infection-related complications) beyond the effect of heat exposure on preterm births.

Figure 4: Heterogeneity in the Effect of Heat Exposure during Last Month of Pregnancy by Adequacy of Prenatal Care Visits Reported by Mothers

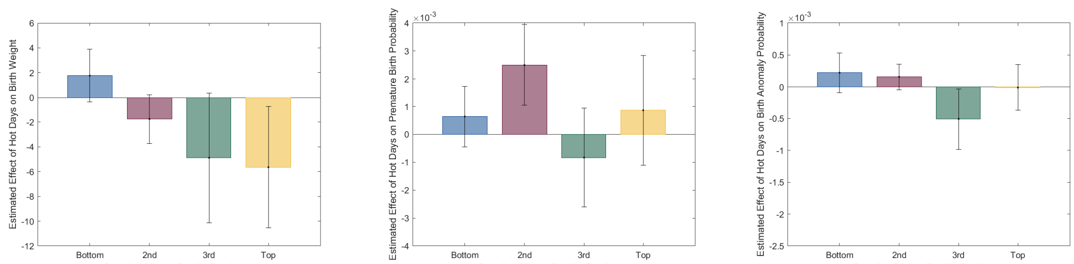


(a) Birth Weight **(b) Premature Birth** **(c) Anomaly at Birth**

Figure 4 presents the heterogeneous effects by pre-natal care visits. We categorize mothers into two groups: (i) those receiving an inadequate number of pre-natal care visits (i.e. less than 7 pre-natal care visits throughout their pregnancy), and (ii) those receiving an adequate number of pre-natal care visits throughout the duration of gestation (i.e. 7 or more pre-natal care visits). Our results indicate that the detrimental effects on neonatal health outcomes such as birth weight and the incidence of anomalies at birth are concentrated among mothers who do not report attending an adequate amount of pre-natal care visits throughout their pregnancy. Altogether, our results presented in Figures 3 and 4 suggest that pre-natal health provision and take-up are essential to mitigate the detrimental effects of extreme weather on neonatal health.

Municipality-Level Differences in Poverty Rates. Figure 5 presents the heterogeneity of our results by the share of the municipality's population enrolled in the Bolsa Familia conditional cash transfer (CCT) program. We implement this heterogeneity exercise to gain some insights on the extent to which part of the detrimental effects on neonatal health can be explained by the lack of sufficient monetary resources to adapt to extreme weather during pregnancy as we take municipality-level participation in the Bolsa Familia CCT program as a proxy for the poverty rate in the municipality.

Figure 5: Heterogeneity in the Effect of Heat Exposure during Last Month of Pregnancy by Quartiles of Programa Bolsa Familia at the Municipality Level



(a) Birth Weight **(b) Premature Birth** **(c) Anomaly at Birth**

The results from this heterogeneity exercise indicates that most of the detrimental effects of heat exposure on birth weight are concentrated predominantly in municipalities with relatively large shares of the population enrolled in the Bolsa Familia program. Nonetheless, we do not observe a similar pattern for the incidence of anomalies or premature births. In further work, we intend to use better proxies of poverty rates/income level at the municipality level to explore the extent to which the detrimental effects of heat exposure are mediated by the lack of monetary resources necessary to adapt to extreme weather conditions.

5 Conclusion

We quantify the effect of in utero heat exposure on neonatal health outcomes and on the incidence of stillbirths. Our results indicate that exposure to excessive heat negatively affects birth weights and increases the incidence of both premature births and complications at birth. Furthermore, we also find a strong link between extreme heat and stillbirths as we find that exposure to an additional hot day increases the number of stillbirths.

Importantly, we exploit the rich microdata on live births to explore the existence of significant gradients in the effects of in utero heat exposure on neonatal health by maternal education, age, and race. We find that the detrimental effects of heat on birth weight are concentrated among mothers from more socioeconomically vulnerable groups (relatively less educated and from minority racial groups) and more physiologically vulnerable groups (relatively older mothers).

We also leverage municipality-level differences in the availability of primary care units specializing in family health (saude familia care units) over time to provide valuable insights regarding the extent to which the availability of this type of primary health care can serve as a mitigating factor against the detrimental effects of in utero heat exposure on neonatal health. Our heterogeneity analysis indicates that most of the detrimental effect of extreme heat on birth weight and the incidence of anomalies at birth is concentrated in municipalities with more limited availability of saude familia care units. Similarly, we find that actual health-seeking behavior in the form of pre-natal care appointments also serve as a significant mitigating factor against the detrimental effects of heat exposure on birth weight, premature births, and the incidence of anomalies at birth.

While our findings on birth weight are consitent with Deschênes et al. (2009) (focused on the context of the United States) and our stillbirths results are aligned with the efects documented in Banerjee and Maharaj (2020) and McElroy et al. (2022), we provide evidence of the impact of heat exposure on a broader set of neonatal health outcomes beyond mortality and birth weight, to also explore effects APGAR scores and the incidence of anomalies at birth (which include complications that can lead to chronic health conditions). To the best of our knowledge, our study provides novel evidence on the detrimental effects of in utero heat exposure on neonatal health by finding the exposure to extreme heat during the last quarter of gestation increases the incidence of neonatal anomalies at birth. Furthermore, our heterogeneity analysis that leverages the unique Brazilian context by exploiting the variation in the availability of family care health units across municipalities and over time provides valuable policy insights regarding the extent to which expansions to the provision of this type of primary care can help mitigate the detrimental effects of extreme weather on newborns' health.

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