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Potential Climate Change Health Risks from Increases in Heat Waves: Abnormal Birth Outcomes and Adverse Maternal Health Conditions

Gulcan Cil[*] and Trudy Ann Cameron[†]

Abstract

We investigate the risks presented by heat waves for adverse health conditions for babies and expectant mothers when these mothers have been exposed to heat waves during gestation or during the period just prior to conception. Rather than just birth weight and gestational age, we focus on less-common metrics such as abnormal conditions in the newborn (fetal distress, reliance on a ventilator, and meconium aspiration) and adverse health conditions in the mother (pregnancy-related hypertension, uterine bleeding during pregnancy, eclampsia, and incompetent cervix). We use monthly panel data for over 3000 U.S. counties, constructed from the confidential version of the U.S. Natality Files for 1989-2008. Our models control for sociodemographic factors and include county, month, and state-by-year fixed effects to control for unobserved spatial and timewise heterogeneity in the data. Even within the U.S., where there is widespread access to air conditioning, heat waves increase in the fraction of babies with abnormal conditions related to maternal stress, as well as the fraction of mothers who experience pregnancy-related adverse health conditions. The scope for these risks in developing countries is likely to be even greater.

Key words: Climate change; heat waves; birth outcomes; infant health; maternal health

JEL Codes: I12, J11, J13, Q54

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1. INTRODUCTION

The latest assessment report by the Inter-governmental Panel on Climate Change (IPCC) states that increases in greenhouse gases in the atmosphere, as well as modifications to land use and land cover over the last fifty years, have led to increases in the frequency and intensity of extreme weather events [(1)]. Given the increasing confidence expressed in that report (and others) that climate change will lead to further changes in the intensity and duration of extreme heat events, policy makers should be concerned about any potentially negative impacts of such weather conditions on human health.

The potential adverse health effects of climate change are one of the strongest motivating factors for policy actions related to climate change. However, the inadequate state of existing knowledge in this area is often cited as one of the key constraints on the implementation of these policies [(2)]. The IPCC explicitly calls for further research on the link between climate change and human health [(3)]. Likewise, the World Health Organization considers investments in research on the potential health impacts of climate change and possible response options as an essential part of adaptation plans [(4)].

Such research, however, requires data. Abundant data are available for the U.S., but this is where one would expect to find the *fewest* health effects from heat waves. As a consequence, if it is possible to find a statistically significant relationship between heat waves and important health outcomes in the U.S., this would imply that the effects in developing countries are almost certainly greater.

This study focuses on birth outcomes as an important category of health effects associated with heat waves. Birth outcomes have been widely analyzed because they represent a health measure that is universally reported and the determinants of newborn health outcomes are not as heavily confounded by other lifetime exposures or health-related behaviors as can be the case for different types of adult morbidity. It is a well-established result in both the medical and economic literatures that there is an association between poor birth outcomes and subsequently worse socioeconomic and health-related outcomes for these individuals later in life (see Currie

[5]; Almond et al. [6], Almond et al. [7]). Fetal development is considered one of the most important factors in a child's later development, and the health and developmental difficulties experienced by many low-birth-weight infants, for example, can impose large costs on families as well as the rest of society, as explained in Almond et al. [8]. Moreover, as supported by empirical evidence, the intergenerational transmission of poor infant health at birth also represents an important source of social costs (see Currie [9]). Therefore, social interventions designed to mitigate harm might optimally be targeted towards pregnant women and/or women of child-bearing age in addition to young children (see Almond and Currie [6]). The same rationale might hold for mitigating risks to these same populations from extreme weather events (such as heat waves) related to climate change.

There is a body of epidemiological literature investigating the impact of external shocks on measures of birth outcomes. The external events considered in these studies include earthquakes, the 9/11 attack and other terrorist attacks, and nuclear reactor and toxic waste accidents (see [10] for a review of this literature). The results in these studies seem to support the contention that experiencing stress from a disaster during pregnancy, even in the absence of a direct exposure or immediate personal impact, can have an adverse effect on pregnancy outcomes.

The psychological and social impacts on pregnant women produced by these various types of natural and anthropogenic calamities may be similar to those caused by extreme weather events. There are studies indicating that women who had been pregnant during or shortly after Hurricane Katrina were at increased risk of mental health problems such as depression and post-traumatic stress disorder (Ehrlich et al. [11]; Harville et al. [12]), and that Hurricane Katrina was associated with an increase in the occurrence of pre-term and low-birth-weight births ([13]; [14]).

Similarly, Zahran et al. [15] find that maternal exposure to Hurricane Andrew resulted in higher risks of fetal distress in Florida, even after adjusting for known risk factors. They argue that maternal stress, and the associated changes in the maternal vascular system, may be an explanation for fetal distress, which is characterized by signs of oxygen deficiency in fetal tissues. They explain that maternal stress—whether it is a physiological stress (such as maternal under-nutrition or malnutrition) or psychological and emotional stress (linked to mothers'

depression, anxiety, or trauma)—may lead to the release of stress hormones such as cortisol. These hormones activate a number of physiological systems that prepare the body for action and respond to stress by diverting blood from other processes, such as reproduction, which are nonessential to immediate action. This can potentially draw vital nutrients and oxygen away from the developing fetus. These authors point out that in cases of excessive stress and resultant high levels of maternal cortisol, when infants are unable to convert cortisol to its inactive forms, high levels of circulating cortisol in the fetus itself can lead directly to a fetal stress response, which in effect may lead to excessive oxygen consumption by the fetus and fetal distress as well as other important adverse birth outcomes.

In a recent study, Currie et al. [16] analyze the effects of severe storms and hurricanes on birth outcomes in Texas over the period 1996 to 2008. They find little evidence of a relationship between exposure to a hurricane during pregnancy and gestation or birth weight, but their findings indicate that mothers living close to a hurricane path during pregnancy were more likely to have some kind of complication during delivery and more likely to have a newborn with abnormal conditions. The abnormal conditions upon which they focus—including assisted ventilation for more than thirty minutes and meconium aspiration syndrome—reflect fetal stress.

The events mentioned above, including hurricanes and storms, are typically thought to affect birth outcomes through direct injuries to the mother or by aggravating maternal stress. Similar mechanisms are likely to be at play for extreme heat events. Moreover, heat waves may affect human health through a variety of different and more-subtle mechanisms. Extreme heat may increase the risks of water-, food- and vector-borne illnesses, and mental, respiratory and diarrheal illnesses. More importantly, exposure to high temperatures increases the risk of acute and chronic health conditions associated with heat stress. These conditions include heat exhaustion, heat stroke, heat rash and heat cramps.

Pregnant women and fetuses might be affected more severely by extreme temperatures than are other people. Findings in the epidemiology literature (see Strand et al. [17] for a review) suggest that pregnant women may be at a greater risk of heat stress. As a result of normal weight gain and the nature of fat disposition during pregnancy, core body temperatures and heat

production tend to be higher among pregnant women. Moreover, disturbed sleep during pregnancy due to heat may also be a significant risk factor for adverse pregnancy outcomes [18].

There are a number of studies in the sociology literature that suggest that socially produced conditions of vulnerability are also important in understanding the link between heat events and human health (e.g. Klinenberg [19]; Duneier [20]). According to these studies, the magnitude of the impact that heat events may have on health depends heavily on the physical and social characteristics of the neighborhoods, and living arrangements. Findings in Browning [21] highlight the importance of social networking opportunities in a neighborhood and access to information about neighborhood functioning in determining the extent of the impact of heat events on health. Such community characteristics may also play a key role in shaping how and to what extent heat wave exposure affects pregnant women.

Several recent studies have examined the relationship between exposure to hot weather and birth outcomes in specific geographic regions. Some examples include original research for two German states by Wolf et al. [22], for Rome, Italy, by Schifano et al. [23] and for Brisbane, Australia, by Strand et al. [24] and Wang et al. [25]. The findings in these studies suggest a link between extreme heat and increased risk of pre-term births. Currie et al. [26] innovate by using a sample of siblings to net out unobserved maternal heterogeneity and find a sharp trough in gestation lengths for babies conceived in May, corresponding to a 10% increase in prematurity. They also find that birth weight tends to be higher for summer conceptions.

A cross-country survey of the effects of meteorological conditions on pregnancy outcomes (preterm birth, birth weight, and preeclampsia) is provided by Laaidi et al. [27], although correlations between environmental conditions, cultural backgrounds, and socioeconomic factors make it difficult to discern the incremental contributions of temperatures alone. Carolan-Olah et al. [28] provide another review of the research and conclude that the weight of the evidence supports an association between high environmental temperatures and preterm births. Beltran et al. [29] review studies concerning seasonal variations in hypertensive disorders of pregnancy (including eclampsia), gestation length, and birth weight. They call for further epidemiological research concerning the relationships between meteorology and adverse pregnancy outcomes.

Two existing papers are most closely related to the present study. Deschênes et al. [30] use earlier near-universal U.S. data on births for the period 1972 through 1988 to examine the effects on birth weights of *ambient* outdoor temperatures during gestation. Their findings indicate that experiencing high temperatures during the second and the third trimester of the pregnancy is associated with slightly lower birth weights. We find no statistically significant effects of heat waves on birth weights. Simeonova [31] likewise uses the U.S. natality data for an earlier period, from 1968 to 1988, aggregated to the county level, combined with climate data on extreme weather events such as thunderstorms, floods and heat, to investigate the effects of these events on birth weights and gestational age at birth. Her findings for heat waves indicate that exposure to a heat wave during the second trimester of the pregnancy is associated with lower birth weight, but heat waves during the third trimester of the pregnancy are associated with *longer* gestation. She does not speculate upon a mechanism that could explain this unexpected effect in the third trimester.

Relative to these closest two earlier studies, we innovate in three main ways. Our first main innovation is to consider a more-recent county/year panel: 1989-2008 rather than pre-1989. An update to the time dimension of the analysis is important for several reasons. First, until the 1980s there are several states that do not report gestational age on birth certificates. Also, in the later time period, there have been more heat waves. Figure 1 shows the overall growth, in the SHELDUS data, in the number of U.S. states reporting at least one heat wave, as well as the number of states reporting at least five heat waves, for the years 1976 through 2014. There have been some modest changes in the way that the National Weather Service designates heat waves over the 1976-2014 period, but the general upward trend nationwide in the SHELDUS data is consistent with the findings for the period 1979-2011 by [32], who examine patterns and trends using a wide variety of alternative heat wave indices.[1] Another difference between the pre-1989

[1] Aggregate monthly SHELDUS data from the Hazards & Vulnerability Research Institute [33] for the total number of *injuries* attributed to heat waves in the U.S., from 1976 to 2014, also show a strongly statistically significant trend in average heat-wave-related injuries of 2.1 per year, with average injuries in January of 1989 being about 40 in June, 193 in July, and 72 in August (although heat wave injuries are not statistically different from zero in other months). The SHELDUS injury counts seem to be the most relevant to the health effects considered in the present study, but a degree of caution is appropriate with the SHELDUS injury data because of increased reporting of extreme-weather-related damage measures over time. The empirical models used in this paper, fortunately, employ year fixed effects which control to a great degree for unobserved factors which systematically affect all counties (including any nationwide discrete changes in National Weather Service criteria for designating heat waves).

period used in earlier studies and our 1989-2008 period is that air conditioning has now become much more widespread in the U.S., in both residential and commercial buildings, compared to earlier years.[2]

Along with examining a more-recent time period—from 1989 through 2008—we consider *all* heat waves that have occurred in the U.S., and investigate their adverse effects on the *entire* population of U.S. births over the same time period. Many of the existing studies which concern the link between extreme weather events and birth outcomes consider the impact of one specific event, e.g. Hurricane Katrina, or a given type of extreme-weather event in a specific geography, e.g. storms in Texas. Or, they use an aggregate time series of historical data on the overall general population, e.g. aggregate data on all births each year from 1968 through 1988. Using more-recent data on the entire population of births, disaggregated down to the county level, may offer a more appropriate estimate of the potential impacts of extreme heat today and in the future.

Conceptually, our empirical approach is analogous to a huge randomized controlled trial, conducted with the general population of the entire country. We assume "treated" populations of pregnant women are those who reside in counties that have been exposed to at least one heat wave during time periods that can be matched roughly to the three months before pregnancy, each of the three trimesters of pregnancy, and (for falsification purposes) for three months after the birth. The "control" populations of pregnant women reside in counties that have *not* been exposed to any heatwaves during each of these five time-periods relative to each birth. In addition to a number of sociodemographic controls, we net out the effects of unobserved heterogeneity via the use of three types of fixed effects. Our use of fixed effects sweeps away biases that would otherwise result from failing to control for systematic differences in risks by region or over time, or systematic differences in susceptibility by women who live in different regions.

[2] Indeed, the use of air conditioning is an important adaptation to more-frequent heat waves. Unfortunately, earlier Census questions about the presence of air conditioners in the household were not included in 1990, 2000 and 2010 decennial censuses, and to our knowledge there are no other sources for data on availability of air conditioners at a level of spatial resolution that would be suitable to incorporate in this study.

Our second main innovation is that, rather than focusing on just the standard birth outcome metrics, we instead emphasize the potential impact of heat waves on a variety of adverse conditions in newborns that can be associated with maternal stress.[3] Birth weight and gestational age have long been the most common measures of health at birth, and a limited number of studies in developing countries have considered these outcomes as a function of extreme heat events. In contrast, we focus on abnormal conditions in newborns such as fetal distress, assisted breathing on a ventilator for more than thirty minutes, and meconium aspiration syndrome. These outcomes may also be linked to subsequent health complications in early childhood or later in life, and thus may also pose a potentially important source of family and social costs to be associated with heat waves.

Our third main innovation is to consider the association between exposure to heat waves during pregnancy and the risk of the *mother* experiencing a pregnancy-related adverse health condition. While heat waves certainly impose significant psychological or emotional discomforts upon many expectant mothers, the stress of these extreme weather events may also have real *physiological* impacts on these women, with consequences that are potentially harmful for the fetus. The set of adverse maternal health conditions that we consider—gestational hypertension, uterine bleeding during pregnancy, eclampsia, and incompetent cervix—are health conditions that mothers may experience *after* they become pregnant. There are two important reasons for analyzing the health complications of the mother during pregnancy.

- These conditions have been shown to be associated, for the mother, with further health complications later in life, and even premature death (although the association may not be causal). For example, women with a history of hypertension during pregnancy are more likely to suffer from diseases related to hypertension later in life, and women with pre-eclampsia during pregnancy are at a greater risk of having cardiovascular diseases and of dying from stroke or ischemic heart disease (see Bellamy et al. [(34)] for the review of this literature).[4]

[3] For completeness, however, we report our results for birth weight and gestational age in our Supplementary Appendix.

[4] Wilson et al. [(35)] classify hypertensive problems during pregnancy into four categories: chronic (pre-existing) hypertension, gestational (transient) hypertension, pre-eclampsia/eclampsia, and pre-eclampsia superimposed on

- Any factor that has an adverse impact on the mother's health during pregnancy potentially affects the fetus and thus the child's future well-being. For example, external shocks to a mother's health during pregnancy as a result of an influenza epidemic have been shown to be associated with inferior future health, education and labor market outcomes for the child (see Almond et al. [36]; Almond [38]).

Although the long-term effects of these specific pregnancy-related maternal health complications and the child's future health and education outcomes are largely unknown, there is certainly evidence in the epidemiology literature about an association between hypertension during pregnancy and lower birth weight and shorter gestation (e.g. Ananth et al. [39]), and between uterine bleeding and pre-term delivery (e.g. Yang et al. [40], Yang et al. [41], and Yang et al. [42]). A better assessment of the nature and magnitude of the impacts of extreme heat on pregnant women is important to the question of how to enhance the effectiveness of climate change adaptation efforts.

In our analyses, we are careful first to establish that heat waves do *not* have a measurable systematic effect on fertility decisions. Our empirical models control for a range of socio-demographic characteristics, time-invariant county characteristics, seasonality of birth outcomes and maternal health conditions, and state-specific changes in birth outcomes and maternal health conditions over time). In terms of the more conventionally investigated birth outcomes, we do find that heat waves during the second trimester of the pregnancy lead to a very small decrease in average gestational age, although heat waves have no statistically significant impact on the fraction of births with low birth weight. In contrast, most of our new evidence for the effects of heat waves on infants and mothers concerns outcomes not typically analyzed. Heat waves do increase the fraction of newborns with abnormal conditions and the fraction of mothers with a pregnancy-related health condition. Furthermore, in falsification tests, we verify that experiencing a heat wave during the three months *after* birth has no discernible effect on any of the birth outcome variables that we consider.

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chronic hypertension, where they define pre-eclampsia as gestational hypertension plus proteinuria of ≥0.3 g/24 hours, and eclampsia as convulsions occurring in the presence of pre-eclampsia.

This study contributes to the broader literature that seeks to identify the extent of the potential adverse human health effects of climate change. The rest of the paper proceeds as follows. Section 2 describes the data. In Section 3, the empirical models and the estimation results are presented and discussed. Section 4 concludes.[5]

2. DATA

Our data on birth outcomes are drawn from the National Vital Statistics System for the period 1989-2008. The Natality data consist of all births registered in the U.S., and include information on each individual newborn, such as gender, month of birth, and birth weight, as well as information on the mother, including health conditions during pregnancy, age, race, marital status and education. We employ the restricted-use version of the data, which identifies each mother's county of residence. We aggregate the natality data on singleton births to the county level so that the unit of observation is a county-month.[6]

Our extreme weather data are drawn from the Spatial Hazard Events and Losses Database for the U.S., which provides county-level spatial resolution for all heat waves that have occurred in the U.S. and have resulted in at least $50,000 worth of damage or one fatality [(43)]. In the data, a heat wave is defined as an unusually hot period whenever the heat index, which combines the temperature with relative humidity, meets or exceeds locally/regionally established advisory thresholds.[7]

We use an earlier and more-detailed edition of the SHELDUS data than is now available for public use. This earlier edition provided records for individual heatwave events for public use, but employed more-stringent criteria for inclusion during 1989-1994 than during later years. Omitted heat waves are those with no attributed fatalities and less than $50,000 in crop or

[5] Additional details are contained in a Supplementary Appendix, to be made available online.
[6] Hawaii and Alaska are excluded. County codes that have changed over time are adjusted. We use the entire population of births in the continental U.S.to take advantage of the geographic variation in heat wave occurrences. The number of observations available in the individual-level data, in conjunction with specifications that involve large number of regressors, recommends aggregation to the county level for computational tractability in finite time.
[7] Thus, there are sometimes discrete shifts in the records for heat waves, particularly across state lines. Fortunately, our use of county and state-year fixed effects absorbs systematic differences in criteria used across different regions.

property damages. We conformed the inclusion criteria for the later years in our sample to match those used in the earlier years.[8]

Despite the variety of hazard variables available in the SHELDUS data, we use only an indicator for whether *at least one* heat wave is recorded for a given county in a given month. We do not attempt to use the SHELDUS data on injuries, deaths, property damages or crop damages to quantify the severity of a heat wave, since the manner in which SHELDUS distributes these losses across counties in the case of multi-county events is less than ideal.

The independent variables of interest in each of the specifications throughout the paper (and in our Supplementary Appendix) are thus simple county-level indicators for the occurrence of a significant heat wave in a given time period. The time periods are constructed relative to the month of birth as shown in Figure 2. The heat wave indicator for the time period that corresponds to the third trimester of pregnancies in a given county, for instance, equals one if the county experienced a heat wave in the birth month or in the three-month period prior to the birth month. Similarly, the heat wave indicator for the second trimester is equal to one if there was heat wave in the county four to six months prior to the birth month (and analogously for the first trimester and the three-month period before conception). As a falsification test, we also include in all of our specifications one three-month period *lead* term (under the logic that events taking place *after* a birth should have no effect on outcomes measured at the time of that birth).

3. EMPIRICAL SPECIFICATION, RESULTS AND DISCUSSION

Heat waves could have an effect on average birth outcomes indirectly if they affect fertility decisions and thereby influence the *composition* of the population of expectant mothers. Models described in the Supplementary Appendix reveal that the mix of attributes among mothers does not depend reliably on the occurrence or non-occurrence of heat waves during any three-month period within the two years prior to the birth month being analyzed. This result suggests that birth outcomes and maternal health conditions can probably be modeled without controlling for systematic selection into the estimating sample.

[8] The public-use 2014 edition of the SHELDUS dataset is only available to subscribers and in aggregated forms. The new data restores the omitted lesser heat events. However, these events are less likely to have resulted in the types of birth outcomes or maternal health effects examined in our study. If included, these more-minor heat events tend to attenuate to some extent the estimated (average-across-severity-of-events) coefficients in our models.

It has been established empirically in the previous literature that birth weight and gestational age can be associated with the socio-demographic characteristics of the mother such as race, education, age and marital status. Although it is reasonable to assume that when and where a heat wave occurs, and its severity, are random with respect to the characteristics of expectant mothers, the level at which mothers are actually exposed to, and affected by, the adverse effects of a heat wave might be influenced by their socio-demographic characteristics (i.e. their ability to avoid the heat). If so, failure to account for mothers' socio-demographic characteristics in the regressions for maternal and neonatal outcomes would allow socio-demographic characteristics to confound the estimates of the effects of heat waves on these outcomes. We find that the socio-demographic *composition* of the set of expectant mothers in a county is not affected systematically by the occurrence of heat waves prior to conception. This allows us to control for these potentially confounding socio-demographic factors in the regressions to explain birth outcomes or material health conditions with minimal concerns about composition/selectivity bias.

As additional covariates in all of our models, we control for the fraction of births in a given county-month to black mothers and other non-white mothers, and the fraction of births to mothers with less than a high school education (omitted category), high school education, and college education. We also control for the fraction of mothers aged less than 18, 18-22, 23-28 (omitted category), 29-34, and 35-and-over, the fraction of married mothers, the fraction of mothers who started prenatal care in the first trimester, the average number of prenatal visits, and the fraction of male babies. To limit any heterogeneity bias from unobserved factors, we also employ county, month and state-by-year fixed effects in our models. These fixed effects account for time-invariant county characteristics, seasonality of birth outcomes or maternal health conditions, and any common state-level changes in birth outcomes or maternal health conditions over the years.

Our generic regression equation is:

$$
Y_{ct} = \begin{bmatrix} \beta_{preconception\_qtr} 1\left(H_{c,t-10}=1 \text{ or } H_{c,t-11}=1 \text{ or } H_{c,t-12}=1\right) \\ +\beta_{trimester1} 1\left(H_{c,t-7}=1 \text{ or } H_{c,t-8}=1 \text{ or } H_{c,t-9}=1\right) \\ +\beta_{trimester2} 1\left(H_{c,t-4}=1 \text{ or } H_{c,t-5}=1 \text{ or } H_{c,t-6}=1\right) \\ +\beta_{trimester3} 1\left(H_{c,t}=1 \text{ or } H_{c,t-1}=1 \text{ or } H_{c,t-2}=1 \text{ or } H_{c,t-3}=1\right) \\ +\beta_{postbirth\_qtr} 1\left(H_{c,t+3}=1 \text{ or } H_{c,t+2}=1 \text{ or } H_{c,t+1}=1\right) \end{bmatrix} + X_{ct}\gamma + \alpha_m + \alpha_{sy} + \alpha_c + \varepsilon_{ct} \quad (1)
$$

where Y_{ct} is any one of the newborn outcome variables or maternal health variables for county *c*, in year-month *t*. The operator $1(\ )$ produces an indicator variable that takes a value of 1 if the argument is true, and is zero otherwise. H_{ct} is an indicator for a heat wave in county *c* and year-month *t*. X_{ct} is the vector of sociodemographic covariates mentioned above, and α_m, α_{sy}, and α_c are month fixed effects, state-by-year fixed effects and county fixed effects. The effects of heat waves during different time intervals relative to birth are thus given by the β coefficients in equation (1).[9]

3.1. Effects of Heat Waves on Newborn Abnormal Conditions

Results described in the Supplementary Appendix show the effects of heat waves on the two birth outcomes that are conventionally addressed—birth weight and gestational age. These effects are either statistically insignificant or very tiny, on average. However, we focus on use of the specification given in equation (1) to analyze the effects of heat waves on the incidence of *other* less-commonly addressed abnormal conditions in the newborn. We consider three types of abnormal conditions: (a) fetal distress, (b) assisted breathing on a ventilator for more than thirty minutes, and (c) meconium aspiration syndrome. Fetal distress is a condition where the fetus shows indications of a deficiency in the amount of oxygen reaching fetal tissues [(44)]. Meconium aspiration syndrome refers to inhalation of meconium by the fetus or the newborn affecting their lower respiratory system.[10] These abnormal conditions are considered to be highly associated

[9] Econometric panel data methods, using fixed effects to control for unobserved heterogeneity, are now considered essential when unobserved heterogeneity might otherwise result in omitted variables bias in key coefficients.

[10] Meconium consists of fetus' "undigested debris from swallowed amniotic fluid, various products of secretion, excretion and shedding by the gastrointestinal tract"[(44)].

with maternal stress and were the focus in studies by Currie and Rossin-Slater [16] and Zahran et al. [15] that investigate the effects of hurricanes on maternal stress.

Our outcome variables reflect the number of births with a given abnormal condition, per thousand births occurring in a given county in a given month. The mean values for the number of births (per thousand) with each abnormal condition are listed in the first horizontal panel of Table I. The most common abnormal condition is fetal distress, which affects on average about 4.5% of all births in a county-month. On the other hand, only 1% of newborns need assisted breathing on a ventilator for more than thirty minutes, and meconium aspiration syndrome affects less than 0.3% of births. Given that these abnormal conditions are fairly rare, we also consider the number of births with *any* of the three abnormal conditions (per thousand births) as an alternative aggregated adverse outcome variable. In the individual-level data, the indicator for "Any one of the three abnormal conditions" is equal to one if the newborn is recorded as having at least one of the three abnormal conditions, and equal to zero if it is known that he/she suffered from none of these three conditions. This indicator is then aggregated to the level of county-months to reflect the number of births (per thousand) with any of these three abnormal conditions.

Vertical Panel A of Table II shows the effects of heat waves on the fraction of births in a county involving three specific abnormal conditions in the newborn: fetal distress, assisted breathing on a ventilator for more than thirty minutes, and meconium aspiration syndrome. Heat waves during the *third* trimester of the pregnancy are associated with an increase in the fraction of births with fetal distress, by about 2.1 per thousand births. There appears to be no statistically significant relationship between exposure to heat waves and the fraction of newborns needing to be placed on a ventilator for more than thirty minutes. However, the results indicate that a heat wave during the *second* and *third* trimesters of pregnancy may be associated with an increase in the fraction of births with meconium aspiration syndrome.

Meconium released into the amniotic fluid during delivery, and the associated increase in the risk of meconium aspiration syndrome, is related to fetal distress [16]. Fetal distress, furthermore, can be created by excessive maternal stress and resultant high levels of maternal cortisol [15]. One potential mechanism through which heat waves may result in elevated maternal

cortisol levels may be dehydration. It has been reported that Ramadan fasting, for example, is associated with increases in maternal cortisol levels [45], and with lower birth weights and reductions in the number of male births (Almond and Mazumder 2011). Dehydration due to restricted fluid intake while fasting might be one reason for this effect. Another mechanism may be the psychological impact that extreme temperatures have on humans. It has been reported in numerous empirical studies that there is a close association between high temperatures and increased aggression and violence that cannot be explained by seasonality of routine activities or by the fact that people are outside more during hot days (see Anderson [46] for a review of this literature). There is empirical evidence that non-aggravated assault and domestic violence increase during extremely hot days (e.g. Butke et al. [47]; Card et al. [48]. Stress levels for some mothers thus may increase indirectly during heat waves if they are subjected to increased aggression and violence at home or in their communities.

Vertical Panel B of Table II shows the effects of heat waves on the fractions of births with *at least one* of the three abnormal conditions itemized above. Exposure to heat waves during all three trimesters of pregnancy now appears to be associated with an increase in fraction of births with at least one of these abnormal conditions. The magnitude of the coefficient for third-trimester heat waves implies that if there is a heat wave in a county during the period that corresponds to the third trimester of the pregnancies, there are on average about three additional babies born per thousand births with at least one of the three abnormal conditions. As shown in Table I, the average number of newborns with at least one of the three conditions in a given county-month is about 83 in 1000 births. This implies that exposure to a heat wave during the third trimester is associated with about a 3.5% increase in the fraction of births with at least one of these three types of abnormal conditions. These results are comparable in sign and timing to the rates estimated by Currie and Rossin-Slater [16] and Zahran et al. [15], who find that hurricane exposure during the first and the third trimesters results in increases in the risk of experiencing either meconium aspiration syndrome or assisted ventilation for more than thirty minutes, and exposure to a hurricane during the second and the third trimesters results in an increase in the risk of fetal distress. The effects of heat waves on maternal-stress-related abnormal conditions in newborns appear to be similar to those of hurricanes in sign and somewhat similar in timing, although the size of the effect is smaller, as would be expected.

3.2. Effects of Heat Waves on Maternal Health Conditions

In addition to causing maternal stress that affects the fetus, heat waves might have an adverse impact on pregnant women themselves through an increased risk of various health conditions. These health conditions might be directly related to the physiological impacts of extreme temperatures, or they might be triggered by complications related to heat stress. Accordingly, we investigate the impact of heat waves on health conditions of new mothers. In the data, there are four conditions that are specific to the pregnancy period: (a) pregnancy-associated hypertension, (b) uterine bleeding during pregnancy, (c) eclampsia, and (d) incompetent cervix.[11] We aggregate the indicators for each condition to the county level, so that the outcome variables are the number of mothers per thousand with the given condition. The mean values given in the second horizontal panel of Table I indicate that pregnancy-associated hypertension is the most common health condition of the four, affecting on average about 4.4% of mothers giving birth in a given county-month. Each of the other three conditions, in contrast, affects less than 1% of mothers.

Using the specification given in Equation (1), we likewise estimate the effects of heat waves during each three-month period going back to one year before the birth. Estimation results are presented in Table III. The results in Panel A indicate that exposure to at least one heat wave during the last two trimesters of a pregnancy is associated with an increase in the fraction of mothers with pregnancy-associated hypertension and eclampsia, whereas heat waves during the first trimester seem to be more closely related to an increase in the fraction of mothers suffering from uterine bleeding during pregnancy.

The results concerning eclampsia are consistent with the findings in epidemiology literature which, as noted earlier, suggest that the prevalence of eclampsia is the highest among women who have been in the second trimester of pregnancy during summer months. Further

[11] These health conditions are defined as follows in the data documentation [(44)]: Pregnancy-associated hypertension is diagnosed when there is an increase in blood pressure of at least 30mm Hg systolic and 15mm Hg diastolic on two measurements taken 6 hours apart after 20th week of gestation. Eclampsia refers to the "occurrence of convulsions and/or coma unrelated to other cerebral conditions in women with signs and symptoms of pre-eclampsia." Incompetent cervix is defined as painless dilation of the cervix in the second or the third trimester characterized by a "prolapse of membranes through the cervix and ballooning of the membranes into the vagina, followed by rupture of membranes and subsequent expulsion of the fetus." Uterine bleeding is any clinically significant bleeding during the pregnancy taking into consideration the stage of pregnancy.

research is needed to understand the biological mechanisms behind the association between extreme heat and hypertension and eclampsia during pregnancy. Uterine bleeding during the early stages of pregnancy appears to be a marker for placental dysfunction [49], but an understanding of the mechanism through which heat waves may result in an increased risk of uterine bleeding will also require further research.

We also consider the effects of heat waves on the number of mothers (per thousand) experiencing any of these four specific adverse health conditions. Similar to the "any of the three abnormal conditions" variable for newborns discussed in the previous section, the indicator for "any of the four health conditions" is equal to one if the mother is recorded as having at least one of the four health conditions, and equal to zero if it is known that she suffered from none of these four conditions. This indicator is aggregated to the county level to reflect the number of mothers with at least one of these four health conditions per thousand mothers giving birth in a given county-month.

Vertical Panel B of Table III indicates that exposure to a heat wave at any time during the pregnancy is associated with an increased risk of at least one of these four health conditions for the mother. For example, the coefficient for 4 to 6 months before birth ($\beta_{trimester\,2}$) implies that a heat wave during the period corresponding to the *second* trimester of pregnancies in a given county-month is associated with about three more mothers (per thousand) suffering from at least one of the four specified health conditions. When compared to the average number of expectant mothers who have at least one of the four health conditions (given in the second horizontal panel of Table I), this corresponds to an approximate 2.6% increase in the fraction of mothers experiencing a pregnancy-related adverse health condition.

4. CONCLUSION

Motivated by concerns about potential increases in infant and maternal health risks as a result of climate change, we have examined whether significant heat waves have any statistically discernible impact on fertility decisions, and whether they seem to increase the risks of a variety of adverse conditions for both newborns and their mothers. Using the U.S. Natality files on birth outcomes and SHELDUS data on heat waves, we find no statistically significant impact of heat

waves on birth *rates* and no robustly significant changes in the racial and educational *composition* of the set of mothers as a consequence of exposure to heat waves (certainly not in the three-month period immediately prior to what would have been the time of conception). These results imply that heat waves do not seem to lead to important changes in *fertility* decisions or strong selection into (or out of) fertility by different socio-economic groups.

This finding is important to the interpretation of subsequent models to explain birth outcomes and maternal health conditions, since it verifies that the composition of the sample of mothers probably does not differ all that much as a result of heat waves. If heat waves were to result in a greater opting-out of fertility by those groups of mothers who are in better health or who have babies with better expected birth outcomes for other reasons, then any negative effect of heat waves on gestational age at birth might be merely a reflection of this non-random selection. Our finding of no strongly statistically significant change in the racial and educational composition of the set of mothers lets us conclude that selection into fertility is probably not driving our findings concerning the association between heat waves, abnormal conditions for the newborn, and adverse health conditions of the mother. Attention to the potential for composition effects is important to any analysis such as this. Subsequent research into the effects of exogenous factors on birth outcomes should certainly take care to establish the independence of fertility decisions from these same exogenous factors.

Given the absence of important composition effects, we then investigate whether heat waves during our updated time interval (1989-2008) continue to have the types of adverse effects found for earlier periods on the most commonly used birth outcome measures: birth weight and gestational age. These results are reported in our Supplementary Appendix. We find only sparse evidence of small impacts on these measures during our sample period. We determine that exposure to heat waves in the *second* trimester of pregnancy has a negative and statistically significant impact on gestational age at birth, but the effects of heat waves on these two most-widely examined birth outcomes are rather subtle. However, we focus in this study on the effects of heat waves on the incidence of abnormal conditions in the newborn that can be related to maternal stress, as well as problems with the mother's health during pregnancy—the effects of

heat waves during pregnancy are more interesting for these other, less-commonly analyzed outcomes.

Our empirical findings do suggest that heat waves have some association with increased risks of maternal stress and adverse health outcomes for both the newborn and the mother. Specifically, we find evidence that babies born in the areas that have suffered heat waves while the newborn was in utero are more likely to suffer from at least one of a set of abnormal conditions at birth (where this set includes fetal distress, ventilator-assisted breathing for more than thirty minutes, and meconium aspiration syndrome). We also find that heat waves during pregnancy are associated with an increase in the risk of at least one of a set of adverse health conditions for the mothers themselves (where this set includes pregnancy-associated hypertension, uterine bleeding during pregnancy, eclampsia, and incompetent cervix).

Methodologically, we make use of large nation-wide panel datasets from two distinct sources, merged at the county level and by month for the entire U.S. We interpret counties experiencing at least one significant heat wave in a given month as quasi-experimentally "treated" cases. We use as "control" cases these same counties in months without heat waves, as well as other counties which never experience heat waves. Our inclusion of three different types of fixed effects in our estimating specifications implicitly sweeps out a wide variety of unmeasured differences across counties and over time. This strategy minimizes potential heterogeneity bias in our estimates that might otherwise distort the apparent effects of heat waves on the health outcomes studied here.

The main contributions of this study are thus three-fold: First, we emphasize the importance of formally assessing whether there is systematic selection into (or out of) fertility in response to heat waves. Any analysis of the average effects of such events across a heterogeneous group must first consider the stability of the characteristics of that group.

Second, the economic literature on the link between ambient temperature and birth outcomes has previously focused mostly on the standard measures of health at birth, specifically birth weight and gestational age. Our findings indicate that, although the effects on these commonly used measures are modest, in-utero exposure to extreme heat does lead to other maternal-stress-related health complications in newborns. Further research is of course needed to

quantify the link between children's experiences with these health conditions as newborns and their future health, education and labor market outcomes.

Third, the findings in this paper suggest that exposures to heat waves during pregnancy pose a risk for the *mother's* health as well. Expectant mothers who experience a heat wave are discernibly more likely to suffer from serious, even life-threatening, health conditions. Measurement of the family and social costs associated with these health conditions, and the collective value to society of avoiding these problems, is also an important issue for future research. Given the link between a mother's health conditions during pregnancy and her future health and birth outcomes, the effects of heat waves on expectant mothers' health should be recognized as a potentially important component of the adverse health effects of extreme temperatures associated with climate change.

Measurable impacts in an advanced economy like the U.S. likely portend even greater impacts in developing countries where people are less likely to be able to rely on technology to adapt to extreme temperatures. Although recent research by Davis et al. [50] predicts a surge in adoption of air-conditioning in middle-income countries within a few decades, diffusion into low-income countries may not occur quickly enough.

To make recommendations for climate change adaptation policies, it will be important to know more about the mechanisms whereby extreme heat events affect both neonatal and maternal outcomes. Even without a precise knowledge of these underlying mechanisms, however, we can conclude that the risks presented by heat waves for birth outcomes and mothers' health must be acknowledged as contributing to the health costs associated with extreme weather events. If heat waves continue to become more frequent, more severe, and more geographically widespread as a result of climate change, the need for this knowledge will only increase.

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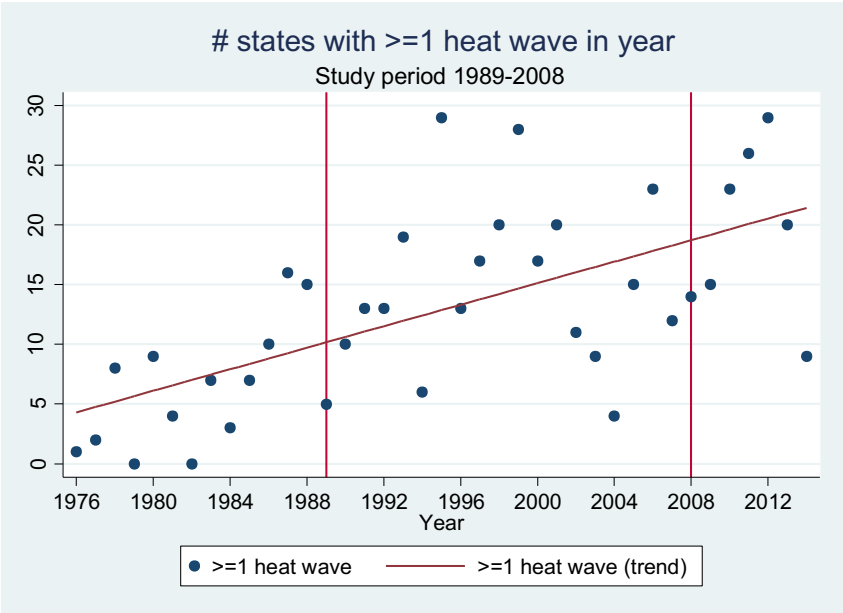
Figures

Figure 1: Increasing prevalence of heat waves in the United States



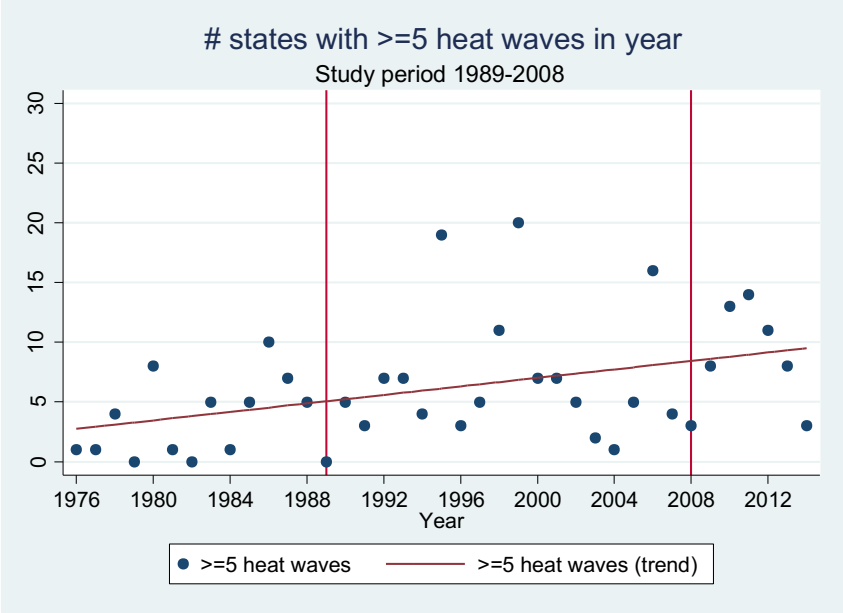
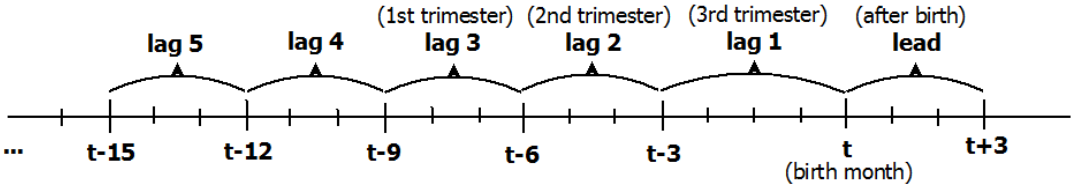


Figure 2: Time-aggregation of county level heat wave indicators and definition of trimesters for the purposes of our analysis



Tables

Table I: Summary statistics: less-conventional types of birth outcomes and maternal health conditions, 1989-2008 (number of babies or mothers per thousand births with the given condition in a given county-month).

Outcomes:	Mean	Std. Dev.	N (county-month)
Newborn abnormal conditions:			
Fetal distress	45.30	70.00	529,415
On a ventilator for more than 30 minutes	10.26	35.57	570,326
Meconium aspiration syndrome	2.539	17.17	570,509
Any of the three abnormal conditions	82.94	175.7	541,961
Maternal health conditions:			
Pregnancy-associated hypertension	43.91	66.06	723,942
Uterine bleeding during pregnancy	8.010	28.62	529,607
Eclampsia	3.82	20.28	723,942
Incompetent cervix	2.402	15.44	570,599
Any of the four health conditions	111.9	233.2	558,934

Notes: Data on the three specific newborn abnormal conditions are not available for the years 2005 through 2008 and are also excluded from the analysis of "Any of the three abnormal conditions". Similarly, data for the maternal health conditions of incompetent cervix and uterine bleeding are not available for the years 2005 through 2008. The analysis of "Any of the four health conditions" also excludes those years of data.

Table II: Newborn abnormal conditions: Effect of heat waves on the number of births (per thousand) with abnormal conditions, selected coefficients for equation (1) (on the heat wave indicators)

	Panel A			**Panel B**
	Fetal distress	On a ventilator > 30 min.	Meconium aspiration synd.	Any of the three conditions
Pre-conception:				
$\beta_{preconception\_qtr1}$	0.913	-0.138	-0.181	1.444
	(0.903)	(0.390)	(0.196)	(1.139)
Pregnancy:				
$\beta_{trimester1}$	1.115	0.007	0.111	2.278*
	(0.918)	(0.408)	(0.240)	(1.199)
$\beta_{trimester2}$	0.957	-0.053	0.371*	2.200*
	(0.849)	(0.364)	(0.212)	(1.126)
$\beta_{trimester3}$	2.074**	0.227	0.406*	2.952**
	(0.951)	(0.396)	(0.229)	(1.222)
Falsification test:				
$\beta_{postbirth\_qtr}$	0.401	0.488	0.274	1.596
	(0.893)	(0.430)	(0.246)	(1.133)
Observations	527,861	569,263	569,446	540,459
Number of counties	3,076	3,077	3,077	3,076

Notes: See notes to Table I. *** p<0.01, ** p<0.05, * p<0.1

Table III: Maternal health conditions: Effect of heat waves on the number of mothers (per thousand) who have experienced pregnancy-related health conditions, selected coefficients for equation (1) (on the heat wave indicators)

	Panel A				**Panel B**
	Pregnancy-associated hypertension	Uterine bleeding	Eclampsia	Incompetent cervix	Any of the four conditions
Pre-conception:					
$\beta_{preconception\_qtr1}$	0.230	-0.144	0.346*	-0.079	0.477
	(0.612)	(0.290)	(0.204)	(0.161)	(1.020)
Pregnancy:					
$\beta_{trimester1}$	0.654	0.837**	0.272	0.010	2.657**
	(0.682)	(0.367)	(0.222)	(0.159)	(1.068)
$\beta_{trimester2}$	1.043*	0.0981	0.417**	-0.086	2.885***
	(0.625)	(0.326)	(0.212)	(0.155)	(1.025)
$\beta_{trimester3}$	1.473**	0.0228	0.303*	0.084	2.302**
	(0.615)	(0.282)	(0.171)	(0.174)	(1.024)
Falsification test:					
$\beta_{postbirth\_qtr}$	-0.290	-0.162	0.120	0.098	1.588
	(0.651)	(0.306)	(0.180)	(0.173)	(1.036)
Observations	722,142	528,057	722,142	569,535	557,415
Number of counties	3,077	3,076	3,077	3,077	3,076

Notes: See notes to Table I. *** p<0.01, ** p<0.05, * p<0.1