Heat Waves: Some Potential Effects of Climate Change on Abnormal Birth Outcomes and Adverse Maternal Health Conditions

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Abstract

Like other extreme weather events, heat waves are likely to occur more frequently worldwide as a consequence of climate change, and their impacts are likely to be borne disproportionately by developing countries. However, detailed data on health outcomes for developing countries over a sufficient period of time are not readily available. Instead, we use monthly panel data for more than 3000 U.S. counties, constructed from the confidential version of the U.S. Natality Files for 1989-2008. We investigate the effects of heat waves on 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). Even within the U.S., where there is widespread access to air conditioning, heat waves increase 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 of these impacts 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

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 Solomon et al. (2007). 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, the negative impact of such weather conditions on human health is a major concern. In high-income countries, many of the health threats presented by heat waves can be mitigated by widespread access to air conditioning technology. In low-income and developing countries with less access to these technologies, however, the human health risks from heat waves can be multiplied greatly.

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 (Pachauri and Reisinger 2007). The IPCC explicitly calls for further research on the link between climate change and human health (Metz et al. 2007). 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 (Scheraga et al. 2003). Such research, however, requires data. Unfortunately, detailed data on important human health outcomes potentially related to heat waves is relatively scarce for developing countries, although these countries are exactly where the health consequences of heat waves are likely to be the most serious. 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.

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 (2009); Almond and Currie

(2011a), Almond and Currie (2011b). 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 society, as explained in Almond et al. (2005). 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 (2011)). 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 [Almond and Currie (2011a)]. The same rationale might hold for mitigating risks to these 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 different measures of birth outcomes. The external events considered in these studies include severe storms and hurricanes, earthquakes, terrorist attacks, and nuclear reactor and toxic waste accidents.[1] Zahran et al. (2010), in particular, considers the physiological mechanisms whereby maternal stress (either physiological or psychological) can affect birth outcomes.

The effects of extreme temperatures, specifically, have been reviewed by Strand et al. (2010). Indirect effects of extreme temperatures through disturbed sleep have been consider by Okun et al. (2009). Exposure to hot weather and birth outcomes in specific localities or regions has been assessed for two German states by Wolf and Armstrong (2012), for Rome, Italy, by Schifano et al. (2013) and for Brisbane, Australia, by Wang et al. (2013).

Strand et al. (2011) survey the epidemiological evidence concerning seasonality in birth weight and preterm birth as well as the effects of prenatal exposure to extreme temperatures. They call for more research "to clarify whether high temperatures have a causal effect on fetal health." Currie and Schwandt (2013) subsequently use a sample of siblings to net out unobserved maternal heterogeneity and find evidence of seasonal differences in birth weights and gestational age at birth.

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. (2011),

[1] Harville et al. (2010) review this literature. Hurricanes Katrina and Andrew have been studied (see Ehrlich et al. (2010), Harville et al. (2009), Xiong et al. (2008), Harville et al. (2010), Zahran et al. (2010) and Currie and Rossin-Slater (2013).

although correlations between environmental conditions, cultural backgrounds, and socioeconomic factors make it difficult to discern the incremental contributions of temperatures alone. Carolan-Olah and Frankowska (2014) 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. (2014) 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. (2009) 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. Simeonova (2011) 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.

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-frequent and more-widespread heat waves. The number of counties that have been affected by heat waves is more than 50% higher during 1989-2008 compared to 1968-1988. Furthermore, in the last two decades, air conditioning has become 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

[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 spatial resolution that would be suitable to incorporate in this study.

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. data on all births from 1968 through 1988. Using more-recent data on the entire population of births, disaggregated to the county level, may offer a more appropriate estimate of the potential impacts of extreme heat today and in the future.

Our second main innovation is that, rather than focusing on 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 social costs 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 psychological or emotional discomforts upon many expectant mothers, these extreme weather events may have real *physiological* impacts on these women as well, 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

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

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. (2007) for the review of this literature).[4]

- 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 [Almond and Mazumder (2005); Almond (2006)].

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 epidemiology literature about an association between hypertension during pregnancy and lower birth weight and shorter gestation [e.g. Ananth et al. (1995)], and between uterine bleeding and pre-term delivery [e.g. Yang and Savitz (2001b), Yang and Savitz (2001a), and Yang et al. (2004)]. 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

[4] Wilson et al. (2003) classify hypertensive problems during pregnancy into four categories: chronic (pre-existing) hypertension, gestational (transient) hypertension, pre-eclampsia/eclampsia, and pre-eclampsia superimposed on 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.

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.

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 (Hazards & Vulnerability Research Institute 2013). 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. Except for the years 1989 through 1994, the SHELDUS data set also includes other events where the total damage is less than

[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.

$50,000 and when there are no fatalities. However, we exclude these additional events during the later period (1995-2008) to conform the data on heat waves across all years.

The independent variables of interest in each of the specifications throughout the paper (and in our Supplementary Appendix) are simple county-level indicators for the occurrence of a heat wave in a given time period. The time periods are constructed relative to the month of birth as shown in Figure 1. 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 decision 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.

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:

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

where Y_{ct} is any one of the newborn outcome variables or maternal health variables for county *c*, year-month *t*. The operator $1(\bullet)$ 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 β coefficients in equation [1].

3.1. Effects of heat waves on newborn abnormal conditions

Results described in the Supplementary Appendix show that the effects of heat waves on the two birth outcomes that are conventionally addressed—birth weights and gestational age—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: (1) fetal distress, (2) assisted breathing on a ventilator for more than thirty minutes, and (3) meconium aspiration syndrome. Fetal distress is a condition where the fetus shows indications of a deficiency in the amount of oxygen reaching fetal tissues (NCHS 1992). Meconium aspiration syndrome refers to inhalation of meconium by the fetus or the newborn affecting their lower respiratory system.[7] These abnormal conditions are considered to be highly associated with maternal stress and were the focus in studies by Currie and Rossin-Slater (2013) and Zahran et al. (2010) 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 1. 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

[7] Meconium consists of fetus' "undigested debris from swallowed amniotic fluid, various products of secretion, excretion and shedding by the gastrointestinal tract" (NCHS 1992).

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 2 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 2.2 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* trimester 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 (Currie and Rossin-Slater 2013). Fetal distress, furthermore, can be created by excessive maternal stress and resultant high levels of maternal cortisol (Zahran et al. 2010). 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 level (Dikensoy et al. 2009), 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 (2001) 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 and Sheridan (2010); Card and Dahl (2011). 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 2 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 the *first* and the *third* 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 1, the average number of newborns with at least one of the three conditions in a given county-month is about 81 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 (2013) and Zahran et al. (2010), 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: pregnancy-associated hypertension, uterine bleeding during pregnancy, eclampsia, and incompetent cervix.[8] We

[8] These health conditions are defined as follows in the data documentation (NCHS 1992): 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

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 1 indicate that pregnancy-associated hypertension is the most common health condition of the four, affecting on average about 4.3% 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 3. 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 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 (Hasan et al. 2010), 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

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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.

with at least one of these four health conditions per thousand mothers giving birth in a given county-month.

Vertical Panel B of Table 3 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 four 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 1), this corresponds to an approximate 3% increase in the fraction of mothers experiencing a pregnancy-related adverse health condition.

4. Conclusion

Motivated by concerns about the potential health impacts of climate change, we have examined whether heat waves have any statistically discernible impact on fertility decisions and whether they seem to have an impact on 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 identifiable 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 sample of mothers probably does not vary much in its composition 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 the negative association between heat waves and shorter gestation 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. 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.

We do 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 the 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, and the effects of heat waves during pregnancy are more interesting for these outcomes.

Our empirical findings do support that heat waves have some association with increased 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 condition 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).

The contributions of this study are three-fold: First, we emphasize the importance of questioning whether there is systematic selection into (or out of) fertility in response to heat waves. Any analysis of the average effects of such events on groups must first consider the stability of the characteristics of those groups. 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 results in 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 more likely to suffer from serious, even life-threatening, health conditions. Measurement of the social costs associated with these health conditions, and the value of avoiding them, is also important 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. Although recent research by Davis and Gertler (2015) 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 adverse impacts of heat waves on birth outcomes and mothers' health must be acknowledged as contributing to the health costs associated with extreme weather events. Given that heat waves appear to have become more frequent, more severe, and more geographically widespread as a result of climate change, the need for this knowledge will increase.

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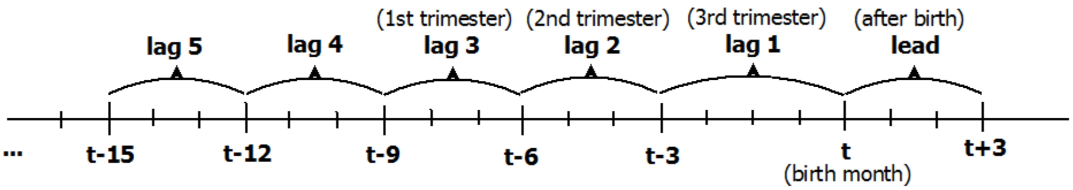
Figures

Figure 1: Time-aggregation of county level heat wave indicators and definition of trimesters for the purposes of our analysis



Tables

Table 1: Summary statistics: less-conventional types of birth outcomes and maternal health conditions, 1989-2008

Outcomes:	Mean	Std. Dev.	N (county-month)
Newborn abnormal conditions:			
Fetal distress	45.37	72.55	581,923
On a ventilator for more than 30 minutes	10.41	37.88	622,823
Meconium aspiration syndrome	2.44	16.91	623,006
Any of the three abnormal conditions	80.6	170.9	594,454
Maternal health conditions:			
Pregnancy-associated hypertension	43.91	66.06	723,942
Uterine bleeding during pregnancy	7.70	28.58	582,101
Eclampsia	3.82	20.28	723,942
Incompetent cervix	2.44	16.39	623,093
Any of the four health conditions	129.5	259.7	623,435

Notes: Each variable indicates the number of babies or mothers per thousand with the given condition in a given county-month. Data on meconium aspiration syndrome, being on a ventilator for more than 30 minutes, fetal distress, incompetent cervix, and uterine bleeding are not available for the years 2007 and 2008. Therefore, the variables for "Any of the three abnormal conditions" and "Any of the four health conditions" also exclude 2007 and 2008.

Table 2: Newborn abnormal conditions: Effect of heat waves on the number of births (per thousand) with abnormal conditions (selected coefficients)

	Panel A			Panel B
	Fetal distress	On a ventilator > 30 min.	Meconium aspiration synd.	Any of the three conditions
Pre-conception:				
$\beta_{preconception\_qtr1}$	0.325	-0.499	-0.122	0.885
	(0.946)	(0.397)	(0.208)	(1.222)
Pregnancy:				
$\beta_{trimester1}$	1.277	-0.395	0.080	2.270*
	(0.972)	(0.414)	(0.235)	(1.270)
$\beta_{trimester2}$	0.540	-0.259	0.350*	1.684
	(0.990)	(0.387)	(0.196)	(1.189)
$\beta_{trimester3}$	2.228**	0.125	0.295	2.815**
	(1.087)	(0.390)	(0.199)	(1.194)
Falsification test:				
$\beta_{postbirth\_qtr}$	0.814	0.647	0.214	1.897
	(1.121)	(0.417)	(0.212)	(1.201)
Observations	580,342	621,734	621,917	592,926
Number of counties	3,076	3,077	3,077	3,076

Notes: See notes to Table 1. *** p<0.01, ** p<0.05, * p<0.1

Table 3: Maternal health conditions: Effect of heat waves on the number of mothers (per thousand) who have experienced pregnancy-related health conditions (selected coefficients)

	Panel A				Panel B
	Pregnancy-associated hypertension	Uterine bleeding	Eclampsia	Incompetent cervix	Any of the four conditions
Pre-conception:					
$\beta_{preconception\_qtr1}$	0.230	-0.103	0.346*	-0.114	1.478
	(0.612)	(0.296)	(0.204)	(0.162)	(1.353)
Pregnancy:					
$\beta_{trimester1}$	0.654	0.831**	0.272	-0.0320	3.492***
	(0.682)	(0.362)	(0.222)	(0.159)	(1.339)
$\beta_{trimester2}$	1.043*	0.374	0.417**	0.0817	3.772***
	(0.625)	(0.382)	(0.212)	(0.222)	(1.322)
$\beta_{trimester3}$	1.473**	0.169	0.303*	0.0869	2.436*
	(0.615)	(0.261)	(0.171)	(0.167)	(1.370)
Falsification test:					
$\beta_{postbirth\_qtr}$	-0.290	0.047	0.120	0.098	1.950
	(0.651)	(0.286)	(0.180)	(0.159)	(1.354)
Observations	722,142	580,524	722,142	622,002	621,889
Number of counties	3,077	3,076	3,077	3,077	3,076

Notes: See notes to Table 1. *** p<0.01, ** p<0.05, * p<0.1

Heat Waves: Some Potential Effects of Climate Change on Abnormal Birth Outcomes and Adverse Maternal Health Conditions

Supplementary Appendix – Online; Not for publication

A.1 Introduction

Our study has assessed the potential importance of systematic selection. We started with an investigation of the potential impact of heat waves on fertility decisions to examine whether exposure to extreme heat leads to selection into (or out of) fertility, or to any robust changes in the socio-demographic characteristics of mothers giving birth.

If there are differential fertility responses to heat waves by different socio-demographic groups, any observed change in birth outcomes might be a result of common or differential changes in fertility or of systematic selection. Using a monthly panel of all U.S. counties, we find that heat waves appear not to be systematically associated with changes in birth rates, where birth rate is defined as the total number of births in a given county-month per thousand women of reproductive age. Also, heat waves do not appear to result in any clear changes in the racial and educational composition of the set of new mothers, which implies that there is no convincing evidence of a significant differential fertility response or endogenous selection into fertility associated with heat waves. Without an appropriate analysis of the effects of heat waves on fertility decisions, it would not be clear whether any implied association between exposure to heat waves and birth outcomes is real, or merely an artifact of selection/composition bias.

To consider the potential impact of heat waves on fertility decisions, we calculate the birth rate in each county-month by dividing the total number of births in a given county-month by the number of women aged 15-44 in that county (in thousands). The overall population data are from Surveillance Epidemiology and End Results (SEER), which provides annual county-level population estimates (by gender and age) for each county.

A.2 Expanded summary of existing literature

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 (Harville et al. 2010a) 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. (2010); Harville et al. (2009)), and that Hurricane Katrina was associated with an increase in the occurrence of pre-term and low-birth-weight births ((Xiong et al. 2008); Harville et al. (2010b)). Similarly, Zahran et al. (2010) find that maternal exposure to Hurricane Andrew resulted in higher risks of fetal distress in Florida, even after adjusting for known risk factors.

Zahran et al. (2010) 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.

Lee (2014) finds that the adverse impacts of maternal stress are even transmitted to the health of that mother's grandchildren. This research investigates the intergenerational influences of maternal stress from the 1980 Kwangju uprising in South Korea, and finds that in utero exposure to maternal stress diminishes the birth weight and the length of gestation for the child's own future offspring, and also increases the risk of low birth weight and pre-term birth. Interestingly, the intergenerational effects of a mother's own in utero exposure to stress were more strongly apparent when her future child was male.

In a recent study, Currie and Rossin-Slater (2013) 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. Heat waves, on the other hand, 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. (2010) 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 (Okun et al. 2009).

Several recent studies have examined the relationship between exposure to hot weather and birth outcomes in specific geographic regions. Some examples include original research based on 300,000 births in two German states, reported in Wolf and Armstrong (2012), that finds weak evidence for an association between season of conception, season of birth or ambient outdoor temperatures, and term low birth weight or preterm birth. However, these effects are not consistent across the two states.

In contrast, the effects of short-term exposure to high and low temperatures and air pollution on preterm births are studied by Schifano et al. (2013) for Rome during 2001-2010. Sociodemographic and clinical risk factors are interacted with these exposures and reveal susceptible subgroups of women. A statistically significant 1.9% increase in daily preterm births per 1 degree C in the two days preceding delivery is estimated for the warm season. A 19% increase in preterm births was observed during heat waves.

Another single-city analysis is provided by Wang et al. (2013) for Brisbane, Australia during 2000-2010. Using proportional hazards models with time-dependent regressors, these authors find that heat waves are significantly associated with preterm births. Currie and Schwandt (2013) 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 by 8-9 grams for summer conceptions.

A number of relevant review articles are also available. Strand et al. (2010) assemble the epidemiological evidence on seasonality in birth outcomes as well as the effects of prenatal exposure to extreme temperatures. Across twenty studies, they report that most find peaks of preterm birth, stillbirth, and low birth weight in winter, summer, or both. They note that the adverse effect of high temperatures appears to be stronger for birth weight than for preterm birth, and they call for more research "to clarify whether high temperatures have a causal effect on fetal health."

The effects of meteorological conditions on pregnancy outcomes are examined in Laaidi et al. (2011), who review 134 articles on the subjects of preterm birth, birth weight, and preeclampsia across many different countries. They note seasonality in these outcomes, explained in part by temperature variations and sometimes by atmospheric pressure, but these variations differ in amplitude and periodicity across countries. An important question is whether any observed effects can be attributed simply to the absolute level of normal-for-season temperatures, or to "heat waves," defined as abnormally hot periods. Correlations between environmental conditions, cultural backgrounds, and socioeconomic factors make it difficult to discern the incremental contributions of temperatures alone.

Carolan-Olah and Frankowska (2014) provide a recent review of over 150 papers and conclude that the weight of the evidence supports an association between high environmental temperatures and preterm births. Rates of preterm birth appear to be linked to heat stress, which may be experienced during extreme heat or following a sudden rise in temperature. Beltran et al. (2014) review 35, 28, and 27 studies concerning hypertensive disorders of pregnancy (including eclampsia), gestation length, and birth weight, respectively, as a function of meteorology. They find that the relative risk of eclampsia is the highest for women who give birth during the month of December (i.e. women who have been in the second trimester of pregnancy during summer months). They also report decreases in gestation length associated with heat, but note that birth weights are lower for deliveries in winter months and in summer months. They call for further epidemiological research concerning the relationships between meteorology and adverse pregnancy outcomes. The present study responds to this need.

There appear to be two studies in the economic literature that explore the effects of heat on birth outcomes. In the first study, Deschênes et al. (2009) use 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. Specifically, they aggregate the station-level average daily temperature data to the county level, and use the number of days during each trimester of the pregnancy in which a county's average daily temperature falls into each of the five temperature bins (from less than 25F to greater than 85F) as the key regressors. 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.

The other study is by Simeonova (2011), who investigates the effects of exposure to several types of natural disasters on gestational age at birth and birth weight. She combines the U.S. natality data for the twenty-year period from 1968 to 1988, aggregated to the county level, with climate data on extreme weather events such as thunderstorms, floods and heat. She then estimates the effects of there having been at least one such event in a county on two outcome variables: the county average of birth weights and county average gestational age. 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.

Finally, 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 (e.g. Almond and Mazumder (2005); Almond (2006)). Although the long-term effects of the specific pregnancy-related health complications that are considered in this study and child's future health and education outcomes are largely unknown, there is certainly evidence in epidemiology literature about an association between hypertension during pregnancy and lower birth weight and shorter gestation (e.g. Ananth et al. (1995)), and between uterine bleeding and pre-term delivery (e.g. Yang and Savitz (2001), Yang et al. (2004)).

Conventional birth outcome variables

For our analysis of the effects of heat waves on birth outcomes, we first considered the effects of heat waves on the most commonly used birth outcome variables: birth weight and gestational age. We aggregate the sample of all singleton births to the county-month level so that the outcome variables are the number of births with low birth weight (per thousand), and the average gestational age of all births in a given county-month. The mean values for these outcome variables (and the other birth outcomes considered in the next sections) are listed in Table A-1.

A.3 Effects of heat waves on fertility and composition of the set of mothers

Before considering either the effects of heat waves on conventional birth-outcome variables or their effects on our newer categories of pregnancy outcomes, we first consider the potential impacts of heat waves on fertility decisions and potential selection into fertility by groups that have historically displayed higher or lower risks of having babies with poor birth outcomes. Heat waves and birth rates (or the educational or racial composition of the set of new mothers) may be linked in two ways: (1) If heat waves lead to miscarriages or abortions in the overall population, then we might observe a decrease in the overall birth rate within a county in response to a heat wave that has occurred within the last nine months in that county. Similarly, if heat waves result in more or fewer miscarriages or abortions in a specific racial group (or in a group of mothers with a certain level education), then there might be a decrease or increase in the fraction of mothers in that racial (or educational) group giving birth in a given county-month in response to a heat wave occurring within the past nine months. (2) Heat waves might also be associated with conception decisions in the overall population or in certain socio-demographic groups. If women (or a subset of women) choose to postpone becoming pregnant in the first place, in response to a heat wave, we could observe a decrease in the birth rate (or a change in composition of mothers) in response to a heat wave that has occurred even *more* than nine months before the month for which the birth rate is calculated.

Our reduced form specifications for the birth rate is designed to reveal whether the number of births per thousand women of child-bearing age in a given county-month varies systematically with the occurrence of heat waves in the past two years. The indicators for heat waves follow the strategy for time-aggregation described in the main text of the paper. To account for unobserved time-invariant county characteristics that are potentially correlated with both fertility decisions and the effects of heat waves, we control for county fixed effects. Finally, we include month fixed effects and state-by-year fixed effects to account for the typical seasonality in birth rates and trends or other unobserved changes in fertility over the years, allowing these changes to be different in each state.

The regression equation is:

$$BirthRate_{ct} = \begin{bmatrix} \beta_{preconception\_qtr5} 1\left(H_{c,t-22}=1 \text{ or } H_{c,t-23}=1 \text{ or } H_{c,t-24}=1\right) \\ +\ldots+\beta_{preconception\_qtr1} 1\left(H_{c,t-10}=1 \text{ or } H_{c,t-11}=1 \text{ or } H_{c,t-12}=1\right) \\ +\beta_{trimester1} 1\left(H_{c,t-7}=1 \text{ or } H_{c,t-8}=1 \text{ or } H_{c,t-9}=1\right) \\ +\beta_{trimester2} 1\left(H_{c,t-4}=1 \text{ or } H_{c,t-5}=1 \text{ or } H_{c,t-6}=1\right) \\ +\beta_{trimester3} 1\left(H_{c,t}=1 \text{ or } H_{c,t-1}=1 \text{ or } H_{c,t-2}=1 \text{ or } H_{c,t-3}=1\right) \\ +\beta_{postbirth\_qtr} 1\left(H_{c,t+3}=1 \text{ or } H_{c,t+2}=1 \text{ or } H_{c,t+1}=1\right) \end{bmatrix} + \alpha_m + \alpha_{sy} + \alpha_c + \varepsilon_{ct} \qquad [1]$$

where the parameters α_m, α_{sy}, and α_c are month fixed effects, state-by-year fixed effects and county fixed effects, and the effects of heat waves, $H_{ct} = 1$, in the same county (during different time intervals) on birth rates in month t are given by the β parameters.

In Panel A of Table A-2, we present our key estimation results for the estimated effects on birth rates in specific county-months, of heat waves prior to that birth month (with up to two years of lags), and in the future (after these births—a falsification test). The first five coefficients and standard errors in vertical Panel A of Table A-2 imply that heat waves are not associated with fertility decisions. That is, the timing of conception appears to be unrelated to heat waves. The universal statistical insignificance of the last four coefficients and standard errors in vertical Panel A of Table A-2 confirms that there is no association between heat waves during pregnancies and the associated *prior* fertility decisions, as should be the case since conception occurs typically in seven to nine months before the birth month. These results suggest that heat waves during pregnancy are not measurably associated with additional miscarriages or abortions.

Although heat waves appear to be unrelated to overall birth rates, there might be differential fertility responses across different socio-demographic groups. To explore whether there is different selection into (or out of) fertility in response to heat waves for different socio-demographic groups, we examine how the racial and educational composition of mothers giving birth in a given county-month changes in response to heat waves. Vertical Panel B of Table A-2 presents our estimates of the effects of heat waves on the racial composition of mothers giving birth in a given county-month. The outcome variables in this pair of equations are the fraction of births to white mothers and the fraction of births to black mothers. If anything, a heat wave one full year previously reduces the likelihood of conception among whites, but it is difficult to identify a plausible mechanism whereby this marginally significant estimated effect could be real. Thus, our estimates do not offer any particularly compelling evidence that heat waves are associated with a statistically significant change in the racial composition of mothers. This suggests that there is likely to be minimal differential selection into fertility by race as a function of heat waves in the pre-pregnancy period.

There may also be differential fertility responses to heat waves for women who have different levels of education. Vertical Panel C of Table A-2 presents the effects of heat waves on the mix of educational attainment among mothers, where the outcome variables are the fraction of births to mothers with less than high school education, mothers with only high school or some college education, and mothers with a college degree or more. It appears that heat waves likewise do not result in systematic selection into fertility that differs by mothers' education. The findings in Table A-2 reassure us that any statistically detectable effects that heat waves may have on birth outcomes are unlikely to be simple artifacts of changes in the composition of the set of mothers.

4.2. Effects of heat waves on birth weight and gestational age

For comparison to other studies, Table A-3 shows the effects of a heat wave in a county on two more-common birth outcome variables: (1) the fraction of births with low birth weight and (2) average gestational age. The estimates suggest that exposure to a heat wave during or before pregnancy has no statistically significant effect on the fraction of births with low birth weight. However, a heat wave during the second trimester of the pregnancy is associated with a statistically significant but tiny decrease in average gestational age. The point estimate for the second trimester can be interpreted as follows: A heat wave during the time period that corresponds to the second trimester of the pregnancy is associated with a little over a three-hour (1.9% of a week) decrease in average gestational age. Thus the effect is statistically significant, but is likely to be of little consequence.

It is worth pointing out, however, that this is the effect on *average* gestational age for all births that have occurred in a given county-month. Expectant mothers living in the same county might have been exposed to the effects of heat waves at varying levels, and the estimated effect is the average across all mothers living in the same county. Although the effects of heat waves on average gestational age appear to be very small, heat waves may have a substantial impact on gestational age *distribution* within a county-month by, for instance, changing the variance or the skewness of the distribution but leaving the mean gestational age relatively unchanged. In an attempt to understand potential impact of heat waves on gestational age distribution, we also used the 5^{th} and 10^{th} percentiles of gestational age in each county-month, rather than the mean (not reported here) as the outcome variables in the specification discussed above. However, the results did not reveal any conclusive impact of heat waves on these lower quantiles of the gestational age distribution.

Table A-1: Summary statistics for conventional birth outcome variables, 1989-2008*

Outcomes:	Mean	Std. Dev.	N (county-months)
Usual birth outcome metrics:			
Low birth weight	60.70	71.36	727,516
Average gestational age in weeks	38.97	0.84	725,662

Notes: Low birth weight measures the number of babies per thousand with low birthweight in a given county-month.

Table A-2: Sample selection assessment: No statistically significant effect of heat waves on birth rate, racial and educational composition of mothers

	Panel A	Panel B		Panel C		
		Fraction of births to		Fraction of births to mothers with		
	Birth Rate	White mothers	Black mothers	Less than high school edu.	High school and some college	College or more edu.
Pre-conception:						
$\beta_{preconception\_qtr5}$	-0.109	0.130	-0.682	-0.210	-0.195	0.405
	(0.095)	(0.764)	(0.605)	(1.166)	(1.469)	(1.154)
$\beta_{preconception\_qtr4}$	-0.122	-1.303*	0.431	-0.256	-0.819	1.076
	(0.107)	(0.777)	(0.647)	(1.169)	(1.545)	(1.229)
$\beta_{preconception\_qtr3}$	-0.167	-0.693	0.640	1.651	-0.323	-1.328
	(0.149)	(0.836)	(0.668)	(1.259)	(1.508)	(1.195)
$\beta_{preconception\_qtr2}$	-0.0952	0.568	-0.944	0.863	0.691	-1.554
	(0.148)	(0.823)	(0.679)	(1.240)	(1.612)	(1.290)
$\beta_{preconception\_qtr1}$	-0.128	-0.084	-0.637	-1.930	1.656	0.274
	(0.138)	(0.794)	(0.670)	(1.270)	(1.614)	(1.304)
Pregnancy:						
$\beta_{trimester1}$	-0.203	-0.783	0.424	-1.177	0.721	0.456
	(0.161)	(0.807)	(0.678)	(1.357)	(1.687)	(1.431)
$\beta_{trimester2}$	-0.125	-0.223	0.118	-0.130	0.581	-0.451
	(0.143)	(0.765)	(0.637)	(1.213)	(1.533)	(1.305)
$\beta_{trimester3}$	0.0283	-0.668	-0.049	-0.179	0.522	-0.343
	(0.120)	(0.712)	(0.588)	(1.133)	(1.435)	(1.112)
Falsification test:						
$\beta_{postbirth\_qtr}$	-0.0577	0.888	-0.689	-0.762	1.431	-0.669
	(0.125)	(0.743)	(0.632)	(1.278)	(1.587)	(1.239)
Observations	738,240	727,521	727,521	725,489	725,489	725,489
Counties	3,076	3,077	3,077	3,077	3,077	3,077

Notes: Robust standard errors in parentheses, clustered at the county level. All regressions include county fixed effects, month fixed effects, and state-by-year fixed effects. Birth rate is the total number of births in a county-month per thousand women of child-bearing age in that county. Fraction of births are calculated by dividing total number of births to mothers with the given characteristic in a given county-month by total number of births in thousand in that county. *** p<0.01, ** p<0.05, * p<0.1

Table A-3: Conventional birth outcome metrics: Effects of heat waves on the number of babies (per thousand) born with low birth weight and on average gestational age in weeks (key coefficients only)

	Fraction with low birth weight	Average gestational age
Pre-conception:		
$\beta_{preconception\_qtr1}$	-0.117	-0.009
	(0.647)	(0.008)
Pregnancy:		
$\beta_{trimester1}$	0.455	-0.006
	(0.690)	(0.008)
$\beta_{trimester2}$	-0.877	-0.019**
	(0.639)	(0.008)
$\beta_{trimester3}$	-0.266	-0.009
	(0.581)	(0.008)
Falsification test:		
$\beta_{postbirth\_qtr}$	0.508	0.000
	(0.740)	(0.008)
Observations	725,090	723,440
Counties	3,077	3,077

Notes: Robust standard errors in parentheses, clustered at the county level. All regressions include controls, county fixed effects, month fixed effects, and state-by-year fixed effects.
*** p<0.01, ** p<0.05, * p<0.1

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