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Temperature, climate change, and fertility

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Abstract

This chapter reviews the empirical literature on the impacts of temperature and climate change on human pregnancies. The focus is on the quasi-experimental studies that use panel data, apply a fixed effect approach, and exploit the random year-to-year fluctuation in temperature. The insights that emerge from the review highlight that exposure to heat in the pre-conception period has detrimental impacts on fertility. In addition, heat during pregnancy increases pregnancy losses, leads to a reduction in gestational length, and lowers birth weight. Despite the growing empirical evidence on the subject, understanding the relationship between temperature and pregnancy-related outcomes is far from perfect. Importantly, the potential impacts of climate change are rarely quantified. The chapter outlines directions for future research.

Keywords: temperature, climate change, fertility, pregnancy, health at birth, birth weight, pregnancy loss

JEL codes: J13, Q54

1 Introduction

Climate change is now considered to be one of the greatest threats for humanity in the twenty-first century. It gained enormous attention not only in the natural sciences but also in the social sciences (Grieneisen and Zhang 2011; Haunschild et al. 2016). The rapid progression of methods used to measure weather effects, combined with increased computing power and the richness of newly available data, has provided abundant evidence on the causal impacts of temperature on human societies (Carleton and Hsiang 2016). Health impacts are among the most analyzed consequences of climate change. Some of these impacts get high publicity and receive a great deal of attention in the academic literature as well, like the increased mortality and morbidity during heat waves and extremely cold temperatures or the threat of climate change-induced spread of vector-borne diseases. However, the impacts of temperature exposure on human pregnancies are among those areas where credible causal evidence is relatively sparse. In addition, understanding the potential effects of climate change is imperfect due to the very low number of projections.

This chapter reviews the literature on the impacts of temperature and climate change on human pregnancies, starting from conception to the birth of the baby. The main focus is on the quasi-experimental (mostly economics) studies that use panel data, apply a fixed effect approach, and exploit the year-to-year variation of temperature (Dell et al. 2014; Hsiang 2016). Spatially specific fixed effects and time fixed effects (that may enter separately by geographic units) can capture time-invariant geographic differences, seasonality, and trends in the outcome variable. As a result, these quasi-experimental studies can adequately identify the causal effects of temperature by relying on the (remaining) unpredictable temperature variations. Nevertheless, public health and epidemiological studies that follow different empirical approaches are discussed as well when the available causal evidence is scarce.

As most papers that study the impacts of temperature exposure focus either on the in utero period or the period before conception, this review discusses these two distinguished exposure periods separately. In addition, the reviewed papers are grouped depending on their main outcome variable. Post-conception temperature exposure (exposure in the womb) can affect the risk of pregnancy loss and the health of the newborns. Pre-conception temperature exposure can influence the probability of conception (and consequently birth rates), albeit it might affect the risk of fetal death and the newborn's health as well.

The attention of this review is limited to temperature's direct effect on pregnancies, fetuses, and newborns. Indirect effects, among others, food production and insecurity, increased conflict, migration,

availability of clean water, newly emerged diseases, are ignored. These pathways might be important as well, but good-quality empirical evidence is often limited. The long-term impacts are also beyond the scope of this review, even though there is credible evidence that outcomes in adulthood are affected by temperature exposure at the time of conception or while in utero (Fishman et al. 2019; Hu and Li 2019; Isen et al. 2017; Wilde et al. 2017).

The rest of the chapter is organized as follows. The next section summarizes the literature on the impacts of temperature exposure before conception. The third section describes the impacts of temperature exposure during pregnancy. The fourth section discusses the projected impacts of climate change. The last section concludes and makes suggestions for advancing the literature.

2 Pre-conception exposure

2.1 Birth rates, conception rates

The seasonality of human pregnancy and its relation to temperature is in the focus of scientific research for many decades (Chang et al. 1963; Mathew 1941; Mills and Senior 1930; Stoeckel and Choudhury 1972; Takahashi 1964). The early works hypothesized a relationship between conception chances (proxied by birth rates) and ambient temperature. They examined the correlation between temperature (at the time of conception) and birth rates in various countries and usually found a negative one. Later studies extended these analyses and estimated a causal relationship by relying on the variation in atypical mean monthly temperatures and using vital statistics data from the United States (Lam and Miron 1996; Seiver 1989). These papers analyzed the impacts separately for US states, therefore, the estimated effects of temperature are somewhat varying. Still, they demonstrated that extreme heat reduces birth rates nine-ten months later. However, these works have some inherent limitations. As average monthly temperatures were used, temperature extremes and their impacts could not be fully captured. In addition, temperature was allowed to affect birth rates only nine or ten months later. Besides, its impact was assumed to be linear or quadratic.

The paper of Barreca et al. (2018) provided a more comprehensive understanding of the temperature-birth rate relationship. Using US data between 1931 and 2010 and applying a fixed effect approach, they studied the dynamics of the impact of temperature exposure over a two-year-long period. They modeled a flexible relationship by entering the entire distribution of mean daily temperatures within a month in the estimation. This study found that each additional >80 °F (~ 27 °C) day, relative to one day between 60 °F and 70 °F (~ 16 -21 °C), decreases the birth rate by 0.06% eight months later, 0.40% nine months later, and 0.21% ten months later. Temperatures below 70 °F (~ 21 °C) have a negligible impact on the birth rate.

Following the initial heat-induced decline in the birth rate, a sizable rebound occurs. Within one year, approximately half of the decline is offset by this rebound. Another remarkable result is that the strength of the temperature-birth rate relationship changes over time. It is getting considerably weaker after the 1960s, and the diffusion of residential air conditioning is reported to be correlated with these changes. In one estimation, Barreca et al. (2018) also calculated weekly conception rates from the birth data (called conception-survival rates) for 1969-2003 and regressed them on the detailed distributions of contemporaneous and lagged temperatures (up to 19 weeks before the time of conception). They found that hot weather has a two-week delayed impact on conceptions: one >80 °F (~ 27 °C) day is estimated to reduce the conception rate by 0.6%. In contrast to their estimation using birth rates, for conception-survival rates, no rebound is observed after the initial drop.

Cho (2020) also examined the effect of temperature on the birth rate and replicated the empirical approach of Barreca et al. (2018). He used monthly data from South Korea for the period of 2009 to 2013 and found ambiguous results, most likely due to the limited time span and, consequently, the low statistical power.

The recent paper of Hajdu and Hajdu (2021a) went one step further and examined the impact of pre-conception temperatures on conception rates between 1980 and 2015 in Hungary. The conception rate was calculated from all clinically recognized pregnancies (live births, induced abortion, miscarriages, stillbirths). They showed that exposure to a day with a mean temperature >25 °C reduces conception rates immediately and up to five weeks after the exposure (compared with a day with a mean temperature of 15–20 °C). The largest impacts are observed between two to four weeks after the exposure: approximately -0.8% for each week. The initial decline is followed by an increase in the conception rate. Roughly half of the short-term decline is compensated by a rebound within six months following the exposure. Separately examining conceptions ending in live births, induced abortions, and spontaneous fetal losses, Hajdu and Hajdu (2021a) showed that the initial drop is very similar for all pregnancy outcomes. However, the subsequent rebound of the overall conception rate is driven by conceptions ending in live births.

What are the mechanisms that can explain the temperature-induced decline in conceptions and births? First, hot temperatures might reduce sexual activity. Evidence suggests that seasonal variation in sexual activity is primarily driven by holidays and cultural/religious celebrations (Markey and Markey 2013; Symul et al. 2020; Wellings et al. 1999; Wood et al. 2017). The direct connection between temperature and sexual activity was rarely examined. Besides, the results of the few existing studies are inconclusive (Hajdu and Hajdu 2019; Wilde et al. 2017). Hajdu and Hajdu (2019) used Hungarian time-use survey data

and found no significant relationship between daily temperature and sexual activity. In contrast, Wilde et al. (2017) reported that both sexual activity and internet searches of sexually-themed expressions decrease with increasing temperature in sub-Saharan Africa. A second potential channel is that hot weather could change conception chances by reducing the reproductive health of women and men. Human studies have shown that exposure to heat suppresses spermatogenesis, have negative effects on various sperm parameters (Ahmad et al. 2012; Brown-Woodman et al. 1984; Garolla et al. 2013; Jung and Schuppe 2007; Mieusset and Bujan 1995; Robinson et al. 1968; Wang et al. 2007; M.-H. Zhang et al. 2015), while animal studies suggest that heat stress might lower the reproductive health of females as well (Hansen 2009; van Wettere et al. 2021). The reported impacts on sperm parameters are prolonged but reversible: the indicators of sperm quality are gradually worsening after the heat exposure but return to the baseline levels at 5-12 weeks after the end of treatment. Third, it has to be noted that the most credible empirical studies on the relationship between temperature and birth rates or conception rates used vital statistics data that includes all births/pregnancies recorded by the health care system. Nevertheless, even these data include only a fraction of human pregnancies, as many conceptions are lost before clinical recognition (Jarvis 2016; Wilcox et al. 2020). Therefore, it can not be ruled out that pre-conception temperature exposure influences the observed conception rate by changing the chance of a clinically unrecognized pregnancy loss in the very early stage of pregnancy.

2.2 Pregnancy loss, health at birth

Pre-conception temperature exposure might affect not only the number of conceptions but also the outcome of the pregnancy. As pre-conception temperature influences the reproductive health of the parents (see above), it might have further consequences on the development of the fetus and the health of the newborn as well. Evidence from human studies is almost non-existent, but animal studies have documented such impacts. Experimental studies on mammals reported that pre-conception exposure to hot temperature increases the chance of both pre-implantation and post-implantation pregnancy losses, irrespectively whether the males or the females were exposed (Baumgartner and Chrisman 1987, 1988; Burfening et al. 1970; Hansen 2009; Mieusset et al. 1992; van Wettere et al. 2021; Wan et al. 2020; Wettemann et al. 1976). In addition, other animal studies suggest that parental exposure to heat before conception might result in a lower weight of the newborn (Jannes et al. 1998; Setchell et al. 1998).

No human studies have provided cleanly identified empirical evidence on the impact of pre-conception exposure to hot and cold temperatures on pregnancy losses or the health of the newborns. Nevertheless, a few papers that studied the relationship between temperature and pregnancy outcomes included an exposure period 10-12 months before births too, which corresponds to the few months just before the

conception for most pregnancies. Some of these papers used data from the African Demographic and Health Survey and showed that the number of pre-pregnancy days with temperature >100 °F (~ 38 °C) is negatively related to the birth weight of the newborn and positively related to the probability of pregnancy loss (Davenport et al. 2020; Grace et al. 2015). In general, similar conclusions emerge from the paper of Grace et al. (2021) using survey data from Mali. However, in contrast to these findings, Wilde et al. (2017) documented a negative relationship between pre-pregnancy temperature and termination of pregnancy using very similar survey data from sub-Saharan Africa.

These results are based on survey data. Birth weight and pregnancy data that are recalled by the women. As a result, measurement errors are likely to be more considerable than in the administrative vital statistics data. Therefore, the signal-noise ratio might be lower, making it more challenging to explore the temperature-birth weight relationship. In addition, in the absence of information on gestation length, the pre-pregnancy period is not determined by the conception date but instead inferred from the birth month. Consequently, pre-conception and post-conception periods are not clearly distinguished. In some cases, the full distribution of temperature exposure is not examined, by which the understanding of the impacts of pre-conception temperatures is restricted. Despite the limitations, these papers provide suggestive evidence on the existence of a relationship between pre-conception temperature and pregnancy outcomes and call for further investigations.

3 Post-conception exposure

3.1 Pregnancy loss

The causal evidence concerning the impacts of temperature exposure during pregnancy on human embryo mortality is very limited. Although many epidemiological studies have examined the association between temperature exposure and the risk of stillbirth or miscarriage (Asamoah et al. 2018; Auger et al. 2016; Basu et al. 2016; Bruckner et al. 2014; Ha et al. 2017; Li et al. 2018; Rammah et al. 2019; Strand et al. 2012; X. Sun et al. 2020), they did not provide causal estimates. Small sample sizes, limited time periods, and case-crossover methodology characterize many of these papers. Importantly, almost all of these studies examined stillbirths, which constitutes only a very small fraction of the clinically observed fetal losses. A recent review of the epidemiological literature concludes that, despite the lack of causal evidence, these studies consistently reported an increased risk of stillbirth associated with exposure to hot and cold ambient temperatures (Sexton et al. 2021).

Davenport et al. (2020) using data for 15 countries from the African Demographic and Health Survey and applying a fixed effect approach, reported that first trimester exposure to >100 °F (~ 38 °C) days increases

the chance of early pregnancy loss (including both induced and spontaneous abortions), whereas exposure to hot days during the third trimester increases the chance of stillbirth. In contrast, Wilde et al. (2017) found no significant relationship between temperature in the first two months of the pregnancy and termination of the pregnancy. Both studies use monthly data without rigorous calculation of the time of conception. Therefore, exposure variables that aim to measure temperature conditions during pregnancy are likely to include temperature before the time of conception as well.

Importantly, all the papers mentioned above had to deal with an obvious data limitation: they could study only clinically recognized pregnancy losses. However, most of the pregnancy losses remain clinically unobserved. These pregnancy losses are missing from any administrative registers, as they occur before a clinical diagnosis, in many cases, even before the woman is aware of the pregnancy. The state-of-the-art estimations of the share of conceptions lost before clinical recognition ranges from 20 to 60% (Jarvis 2016; Wilcox et al. 2020). As the share of these clinically undetected pregnancy losses is remarkably high, it is essential to study them to understand the impact of temperature exposure on embryo mortality completely.

A recent paper used an indirect empirical approach to study the effect of early pregnancy temperature exposure on the clinically unobserved pregnancy loss rate (Hajdu and Hajdu 2021b). It used administrative data of the clinically observed pregnancies (live births, induced abortions, miscarriages, and stillbirths) from more than three decades for Hungary and utilized the impossibility of backward causation. In this setting, the impossibility of backward causation means that post-conception temperature is not able to change whether the conception occurs or not but can change its outcome (e.g., from a clinically observed outcome to a clinically unobserved pregnancy loss). The authors argue that if the post-conception temperature is observed to change the number of conceptions calculated from vital statistics data, it has to be equaled by a similar change with the opposite sign in the number of clinically unobserved pregnancy losses. That is, the effects of temperature exposure during early pregnancy on the clinically unobserved pregnancy loss rate can be inferred from the estimated impacts on the conception rate calculated from clinically observed pregnancies. The authors found that exposure to hot temperatures during the first few weeks after the conception increases the clinically unobserved pregnancy loss rate, whereas exposure to colder temperatures decreases it. Importantly, the estimated impacts are not due to a change between the number of clinically observed and clinically unobserved pregnancy losses. In other words, heat does not simply cause a shift in the timing of some pregnancy losses but changes their outcome, increasing the total number of pregnancy losses (clinically observed and unobserved).

3.2 Health at birth

Although there is abundant literature on the relationship between indicators of health at birth and in utero temperature exposure, only a few of them are from the recently emerged economics literature that exploits high-frequency changes in temperature to identify causal effects. The studies can be distinguished by the outcome variables. This review focuses on the two most common indicators of health at birth: birth weight and gestation length. Gestation length (and preterm birth) is studied mainly in the epidemiological literature, whereas birth weight is examined in the economics literature as well.

Most of the existing studies on the relationship between temperature and gestation length/preterm birth report associations (Basu et al. 2010; Cox et al. 2016; Strand et al. 2012; S. Sun et al. 2019; Vicedo-Cabrera et al. 2014). Recent reviews concluded that these studies suggest that hot weather during pregnancy triggers the occurrence of preterm births (Chersich et al. 2020; Y. Zhang et al. 2017). However, these papers provided an incomplete picture, not only because of the lack of causal evidence but as near-term displacements of preterm births were not taken into account (Barreca and Schaller 2020). They did not explore whether a higher number of preterm births in hot periods is due to a shift of births that would have qualified as preterm even in the absence of exposure to heat.

The paper of Barreca and Schaller (2020) advanced this literature. Their sample covers 56 million births from the United States and spans the 1969-1988 period. It applies a novel approach: uses daily birth rates to quantify the loss of gestational days due to hot temperatures during the last weeks of pregnancy. Including temperature lags, the authors could quantify the shifts in daily birth rates. They showed that birth rates increase by 0.97 births on days with a maximum temperature ≥ 90 °F (~ 32 °C), compared with a 60–70 °F (~ 16 -21 °C) day. Birth rates are also increased (by 0.66 births) on the day following the exposure to a ≥ 90 °F day. In general, the higher the temperature, the higher the contemporaneous birth rate, but this relationship is stronger at the higher end of the temperature scale. However, two days after exposure to heat, birth rates are substantially decreased, and the impacts remain negative in the first two weeks following heat exposure. This pattern is clear evidence of a shift in the delivery date. The sum of the coefficients of the lagged temperature variables is basically zero after 14-15 days, which suggests that the temporal displacement of deliveries is within two weeks after exposure to heat. The authors also calculated the average loss of gestation per affected infant and found that one additional hot day results in 6.1 lost gestational days per infant.

Another few papers examined the relationship between temperature exposure during the whole pregnancy period and gestational length or chance of preterm birth applying a fixed effects approach. The study of Andalón et al. (2016) using administrative data for Colombia over the period of 1999-2008 showed that

exposure to heat in at least one month during pregnancy leads to an increase in the probability of preterm birth, whereas exposure to cold has an opposite impact. In contrast, using data for New York for 1985-2010, Ngo and Horton (2016) found negligible impacts on gestational age.

The seminal paper of Deschenes et al. (2009) is the first that provided a causal estimate on the impact of in utero temperature exposure on birth weight. It is based on a fixed effects approach, exploits the unpredictable year-to-year temperature fluctuations, and uses individual-level data on more than 37 million US births between 1972 and 1988. The exposure period is calculated from the inferred date of conception and is independent of the actual length of pregnancy, as gestation length might be influenced by exposure to extreme temperatures. Temperature is allowed to have a nonlinear effect on birth weight. The authors found that exposure to an additional day with a mean temperature >85 °F (~ 29 °C) causes a decrease in birth weight, compared with a 45-65 °F (~ 7 -18 °C) day. The impacts range in magnitude from 0.003% to 0.009%, with larger effects in the second and third trimesters. Cold temperatures are reported to have much weaker impacts. Importantly, blacks seem to be affected more strongly than whites.

Following the paper of Deschenes et al. (2009), numerous studies analyzed the impacts on birth weight applying a similar methodology. They analyzed data from different countries of the world, used different temperature thresholds, but the general conclusions are the same: heat reduces birth weight. Ngo and Horton (2016) estimated the impacts of extreme temperatures on birth weight in New York using birth certificate data from 1985 to 2010. They reported that exposure to extreme heat or cold reduces birth weight. Chen et al. (2020) used data on more than 600,000 singleton births from rural areas of China for 1991-2000. They found that, relative to a day in the 0–4 °C temperature range, extreme heat (daily mean temperature >28 °C) reduces birth weight by 0.057%, but cold temperatures have no impact. Hajdu and Hajdu (2021c) used administrative data on more than 1.5 million singleton live births conceived between 2000 and 2016 in Hungary. They showed that exposure to one additional hot day (mean temperature above 25 °C) during the gestation period reduces birth weight by 0.46 g, relative to a 15–20 °C day. The impact of a 20–25 °C day is -0.36 gram, whereas colder temperatures seem to have positive but small and statistically insignificant effects on birth weight. Grace et al. (2021) examined only the impacts of hot days (daily maximum temperature is >100 °F, ~ 38 °C). Using Malian survey data from 2000, 2006, and 2012, they concluded that newborns' birth weight is lower when exposed to more days over 100 °F (~ 38 °C) (and less ≤ 100 °F days). Similar conclusions emerged from the papers of Grace et al. (2015), Davenport et al. (2020), and Bratti et al. (2021) using survey data for multiple countries in Africa.

A slightly different approach was followed by others (Andalón et al. 2016; Molina and Saldarriaga 2017). These papers defined exposure to heat/cold not by absolute thresholds but as a “large” deviation between

the monthly temperature and the long-term mean in units of the standard deviation (SD). In other words, they calculate temperature z-scores. Andalón et al. (2016) used administrative data for rural and semirural areas of Colombia over 1999-2008. Their analysis sample covers approximately 1.2 million births. They found that exposure to heat (the monthly temperature is above 0.7 SDs from the long-term mean during at least one month during pregnancy) decreases birth weight, while cold (the monthly temperature is below 0.7 SDs from the historical mean during at least one month during pregnancy) has no effect. Examining the intensity of heat by using more categories (0.7–1.0 SDs, 1.0–1.5 SDs, 1.5–2.0 SDs, and >2.0 SDs) gave slightly puzzling results: e.g., the coefficient of the highest category is positive. Molina and Saldarriaga (2017) used survey data for Bolivia, Colombia, and Peru over the period 1990–2013. They found that when the monthly average temperature during pregnancy is 0.5-1.5 SDs above the historical mean, birth weight is reduced by 20 grams. When the temperature is observed to be above 1.5 SDs relative to the historical mean, birth weight is reduced by more than 60 grams.

Although the abovementioned studies agree that heat exposure lowers birth weight, they disagree about which trimester of pregnancy is most sensitive to hot temperature. Some of them find apparent differences, while others conclude that there is no significant variation across trimesters. It has also remained unanswered whether the reduced birth weight following exposure to heat is simply due to a reduction in gestational length or the inadequacy of fetal growth plays an important role. Some estimations that include the gestational length as a control variable find that it does not considerably change the results, which suggests that slower intrauterine growth might be an important mechanism. However, as gestation length is usually available in completed weeks, in many cases, a small reduction in actual gestational length does not change the reported length of pregnancy. That is, controlling for reported gestational length might be an imperfect test of this question.

It should also be highlighted that the estimations discussed in this subsection are likely to be based on positively selected samples of newborns. As the previous subsection has shown, temperature exposure during pregnancy changes the composition of fetuses that survive to live birth. The selection is unlikely to be random, but rather fetuses with below-average health are likely to be removed (Almond and Currie 2011; Bruckner and Catalano 2018; Catalano et al. 2012). Although several papers recognize this selection and its influence on the estimates of the temperature effects, none of them tried to estimate the magnitude of the bias from selective mortality. Nevertheless, many of the papers note that their estimations should be considered as a lower bound of the scarring effect of temperature exposure on indicators of health at birth. Note that a similar selection process might influence estimates of the impacts of pre-conception temperature on pregnancy loss and health at birth.

4 The impacts of climate change

The studies reviewed in the second and third sections show how temperatures affect the chance of conception, the outcome of the pregnancy, and the health of the newborns. Combining the estimated temperature effects with outputs of climate models, the future impacts of climate change can be predicted. Surprisingly, only a few studies make this step, even though the quantification of consequences of future temperature changes is fundamental for effective policymaking.

Hajdu and Hajdu (2021a) used projections from 21 climate models in the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) dataset to estimate the impact of climate change on the conception rate for Hungary. They compared the predicted temperature distribution at the middle of the 21st century (2040–2059) to a historical baseline (1986–2005) in the NEX-GDDP data. To account for climate uncertainty, they used within-model changes for the 21 climate models. They also considered regression uncertainty by resampling regression coefficients. The observations were sampled 500 times with replacement, and the relationship between temperature and the conception rate was re-estimated in each sample. In this way, 10,500 projections of the impact of climate change were created (21 climate models \times 500 coefficient vectors), by which they fully accounted for both climate and regression uncertainty (Burke et al. 2015). The impacts were forecasted under two representative concentration pathway (RCP) scenarios: RCP 4.5 and RCP 8.5. RCP 4.5 is an intermediate scenario with declining greenhouse gas (GHG) emission and stabilizing GHG concentration in the second half of the twenty-first century, whereas RCP 8.5 represents a scenario where GHG emission and concentration continue to rise (Moss et al. 2010). The calculations showed that the range containing 95% of the projections spreads from -1.49% to -0.20% for RCP 4.5 and from -1.92% to -0.26% for RCP 8.5. But there are sizeable seasonal differences: summer and early autumn conceptions are projected to decline, whereas conception rates are projected to increase in the first calendar weeks, and especially in the last ten weeks of the year.

Regarding the impacts of climate change on health at birth, Deschenes et al. (2009) used temperature projection of the National Center for Atmospheric Research Community Climate System Model (CCSM) 3 for the years 2070–2099 (under the A2 scenario, which is at the higher end of the emissions scenarios) and compared it with the temperature data drawn from the National Climatic Data Center for the years 1972–1988. The authors projected that climate change would lead to a decrease in average birth weights of 0.22% or 7.5 grams for whites and 0.36% or 11.5 grams for blacks in the US. However, their approach has fundamental shortcomings (Auffhammer et al. 2013; Burke et al. 2015). First, only one climate model was used. Thus, the uncertainty of long-term climate projections is underestimated. Second, future temperatures were not compared to retrospectively simulated (modeled) temperatures but to observed

temperatures. Therefore, the difference between the forecasted and baseline temperatures does not simply reflect the projected temperature changes but incorporates a bias that stems from the fact that projections of climate models differ from the observed historical patterns. Third, the uncertainty in terms of the relationship between temperature and birth weight was ignored.

Ngo and Horton (2016) took outputs from 33 climate models derived from the fifth phase of the Coupled Model Intercomparison Project (CMIP5) of the World Climate Research Programme (WCRP) and projected the impact of climate change on birth weight under RCP 4.5 and 8.5 for New York. The median projections show a small reduction in birth weight in the 2070–2099 period in the business-as-usual scenario (RCP 8.5) and a positive impact in the RCP 4.5 scenario. Although these projections account for climate uncertainty, regression coefficients are fixed at their point estimates. Consequently, regression uncertainty in the historical relationships was not taken into consideration.

Hajdu and Hajdu (2021c) accounted for both climate and regression uncertainty and projected a sizeable decline in birth weight by the mid-21st century in Hungary under the RCP 8.5 scenario. These calculations were based on within-model changes in temperatures between the 1986–2005 and 2040–2059 periods (outputs of 21 climate models of the NEX-GDDP dataset). Their median projection suggests a decline of 15.3 grams, while the range containing 99% of the projections is between –34.2 and –4.3 grams. The authors also showed that the impacts on births conceived in different parts of the year are considerably different. The impacts are projected to be more severe for births conceived during the winter and spring months. The median projection for this period is approximately –20 grams, whereas it is below –10 grams in the late summer/early autumn.

Barreca and Schaller (2020) projected the impacts of climate change on lost days of gestation for the US. The authors took outputs from 22 climate models (from CMIP5) and calculated the within-model changes (under the RCP 8.5 scenario) in the temperature distribution between the 2000–2019 and 2080–2099 periods. The average changes across the 22 climate models project that there will be approximately 316,000 additional lost days of gestation per year in the US. Unfortunately, regression uncertainty was left out of the projections.

Ignoring regression or climate uncertainty makes the projected impacts seem more precise than they actually are, but other factors should also be considered when interpreting these projections. First, these projections assume that the future relationship between temperature and the conception rate/birth weight/etc. will be the same as in the past. However, adaptation may occur in the future. Therefore, projections that rely on historical estimates might overestimate the impacts of climate change. Second, observable temperature exposure might be insufficient to inform us about the impacts of extreme

warming that are beyond human experience. As many studies have observed, the impact of temperature is often nonlinear. Therefore, the impacts of previously unexperienced extreme temperature events might be considerably underestimated by the historical relationship. Third, the projected impacts of climate change do not completely incorporate the indirect costs of change in temperature. Hotter climate, intensification of extreme events, prolonged exposure to heat is likely to affect agricultural yields, migration, conflicts, stress, drinking water shortage, the habitat of pathogens and vectors. These changes are likely to influence human pregnancies and the health of newborns, but they are not fully covered by the historical estimates based on the short-run variation of weather. Fourth, climate change is more than simply the change in temperature distribution. Long-run warming might be accompanied by changes that occur only once critical thresholds are crossed (e.g., rapid sea-level rise, changing precipitation patterns, changing humidity, intensification of storms). In sum, as Dell et al. (2014) note, the projected impacts “are neither obviously an upper bound nor a lower bound for the effect of climate change” (p. 773). Depending on which factor dominates, the projected impacts might be larger or smaller than the “actual” impacts.

5 Summary

This chapter has provided an overview of research on the impact of temperature and climate change on human fertility. The focus has been on the quasi-experimental studies that use panel data and apply a fixed effect approach. Exploiting the random year-to-year fluctuation in temperature, they can identify the causal effects of temperature. Although several important insights emerged from these studies, the understanding of the temperature-fertility relationship is far from perfect.

First, future research should examine how the effects of temperature vary with the local climate. It could provide important insight regarding the potential role of adaptation in the future. Regarding mortality, several papers carefully demonstrated that there is considerable heterogeneity in temperature effects by climate, and incorporating this heterogeneity into the prediction of the impacts of climate change could substantially change the estimations (Carleton et al. 2020; Heutel et al. 2020). In terms of human pregnancies, evidence is sparse and is entirely from the United States. Barreca et al. (2018) showed that the impact of heat on birth rates is stronger in US states with a cooler climate. Barreca and Schaller (2020) presented similar results for gestational length.

Second, for many fertility-related outcomes, current evidence is from high-income countries. Only for the impact of in utero temperature exposure on birth weight is there evidence from worldwide, including North and South America, Africa, Europe, and Asia. Nevertheless, even in this case, future studies should

be conducted on multi-country samples applying the very same methodology to provide results that are comparable across countries with lower or higher income.

Third, the impacts of extreme temperature events, like heat waves, should receive much more attention. Due to climate change, prolonged exposure to heat will rise fast in the next decades. The impacts of an extremely hot day might be substantially stronger if it is preceded by other scorching days.

Fourth, future research also should examine how the impact of temperature has changed over time and how the changes might influence the estimates of the impacts of climate change. A few studies suggest that temperature's current effects might be weaker for some outcomes than some decades earlier (e.g. Barreca et al. 2018).

Fifth, the moderating effects of other weather variables and environmental factors should be examined, like humidity or air pollution. Humidity makes the ambient temperature feel warmer or cooler. Thus, it could influence the temperature impacts, whereas a high level of air pollution may exacerbate the effects of heat.

Sixth, we need a better understanding of the relationship between in utero temperature exposure and health at birth. Selective mortality after exposure to heat is likely to influence the estimation. What is the magnitude of the bias from in utero selection?

Seventh, the number of projections regarding the impacts of climate change is surprisingly limited. Although the impacts of temperature on human fertility are analyzed by a growing number of studies, to provide inputs for the development of public policies, these estimations should be combined with projections from climate models. Importantly, in these calculations, both climate and regression uncertainty should be considered, and the underlying assumptions and the limitations of the projections should also be clarified.

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