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Climate change and the mortality of the unborn

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ABSTRACT

Although previous studies have examined the association between temperature exposure and pregnancy losses (mainly focusing on the risk of stillbirth), causal estimates are still missing. The literature also lacks projections on the impacts of climate change. Using Hungarian administrative data spanning 1984 to 2018, this paper estimates the effect of temperature on the weekly spontaneous pregnancy loss rate. We show that, compared to a mild temperature, heat causes a substantial increase in the risk of pregnancy loss, whereas cold temperatures slightly decrease it. These impacts are not due to near-term displacement of some pregnancy losses but represent changes in the pregnancy outcomes. Combining the estimated effects with outputs of thirty climate models implies that climate change will increase the spontaneous pregnancy loss rate in the 21st century. The risk of pregnancy loss will be especially elevated during summer.

1. Introduction

The rapid progression of empirical methods used to measure the causal effects of weather, combined with the richness of newly available data and increased computing power, has provided abundant evidence on how climatic conditions influence human societies (Carleton and Hsiang, 2016; Dell et al., 2014). An important strand of this rapidly growing climate economics literature examines the impacts of temperature exposure on pregnancy-related outcomes: conceptions, birth outcomes, and infant health (for a review see Hajdu and Hajdu, 2022a). It is well documented that exposure to heat before and around the time of conception causes a decline in the number of conceptions and, consequently, birth rates (Barreca et al., 2018; Hajdu and Hajdu, 2022b), whereas hot weather during pregnancy decreases birth weight and leads to shorter gestation (Andalón et al., 2016; Barreca and Schaller, 2020; Davenport et al., 2020; Deschênes et al., 2009; Grace et al., 2021; Hajdu and Hajdu, 2021a; Ngo and Horton, 2016; Sun et al., 2019; Conte Keivabu and Cozzani, 2022).

However, causal evidence about the effects of temperature exposure on spontaneous pregnancy losses (defined as spontaneous pregnancy demise during any stage of the pregnancy, including early pregnancy losses, miscarriages, and later fetal deaths) is still very limited. As many as 40–67% of all conceptions end in a spontaneous pregnancy loss, but many of them remain clinically unobserved (Jarvis, 2016; Wilcox et al., 2020). Around 10–15% of clinically recognized pregnancies end in spontaneous pregnancy loss. The vast majority of them occur before 20–28 completed weeks of gestation (miscarriages), whereas around 1% of the clinically observed pregnancies end in stillbirth (Blencowe et al., 2016; Hug et al., 2021; Quenby et al., 2021; Rai and Regan, 2006; Regan and Rai, 2000). An estimated 23 million miscarriages and 2–2.6 million stillbirths per year occurred in the second half of the 2010s worldwide (Blencowe et al., 2016; Hug et al., 2021; Quenby et al., 2021). Spontaneous pregnancy loss is not only a common pregnancy outcome,

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but it is associated with sizable economic costs, psychological and obstetric consequences. For example, the annual economic cost of miscarriage is estimated to be £471 million (in 2018 prices) in the UK (Quenby et al., 2021), but it does not include the monetary costs of the short- and long-term psychological and medical consequences. Most women and their partners experiencing miscarriage or stillbirth suffer from anxiety, stress, depression, or other psychiatric symptoms that may persist for many months or even years after the loss (Cacciatore, 2013; Kersting and Wagner, 2012; Lok and Neugebauer, 2007; Robinson, 2014). Parents after a pregnancy loss have an increased risk of marriage dissolution (Gold et al., 2010; Shreffler et al., 2012). Besides, miscarriage and stillbirth are associated with adverse obstetric outcomes in subsequent pregnancies (Quenby et al., 2021; Regan and Rai, 2000; van Oppenraaij et al., 2009).

The majority of previous studies have examined the association between temperature exposure and the risk of stillbirth (Auger et al., 2017; Basu et al., 2016; Bruckner et al., 2014; Ha et al., 2017; Li et al., 2018; McElroy et al., 2022; Rammah et al., 2019; Strand et al., 2012), and a couple of papers have analyzed the association of ambient temperature with miscarriage risk (Asamoah et al., 2018; Sun et al., 2020). These papers usually reported an increased risk of fetal death associated with exposure to hot ambient temperatures (for a review, see Sexton et al., 2021).

Importantly, existing studies are almost entirely from environmental epidemiology, while economists have paid little attention to the mortality of the unborn until now. The scarcity of causal estimates on fetal deaths is especially surprising, as the impact of temperature on mortality, including infant mortality, is a major theme in the empirical climate economics literature (Banerjee and Maharaj, 2020; Barreca et al., 2016; Barreca, 2012; Carleton et al., 2022; Cohen and Dechezleprêtre, 2022; Deschênes and Greenstone, 2011; Deschênes and Moretti, 2009; Geruso and Spears, 2018; Hanlon et al., 2021; Heutel et al., 2021; Karlsson and Ziebarth, 2018; Mullins and White, 2020; Otrachshenko et al., 2018; Yu et al., 2019). These papers usually rely on panel data, account for spatial differences, time trends, and seasonality, and exploit the exogenous year-to-year variation of temperature, therefore, they can adequately identify the causal effects of temperature (Dell et al., 2014; Hsiang, 2016).

Studying the relationship between temperatures and pregnancy losses, only a handful of papers followed this approach. Two studies used survey data from Africa, and examined the relationship between temperature and termination of pregnancy (without distinguishing between spontaneous and induced abortions) (Davenport et al., 2020; Wilde et al., 2017). The results are contradictory. Davenport et al. (2020) reported that the likelihood of early induced/spontaneous abortion rises as the proportion of hot days increases in the first trimester. A similar effect was estimated for the probability of late pregnancy loss in the third trimester. In contrast, Wilde et al. (2017) estimated a negative (but statistically insignificant) relationship between temperature in the first few months of the pregnancy and termination.

Causal evidence is also available for preclinical pregnancy losses that occur in the first few weeks of pregnancy (before clinical recognition). A recent study used administrative data from Hungary with complete coverage of the clinically observed pregnancies (Hajdu and Hajdu, 2021b). The authors utilized that temperature exposure after the conception is not able to change whether the conception occurs or not (impossibility of backward causation) but can change the outcome of the pregnancy. They have shown that exposure to hot temperatures during the first six weeks after conception increases the clinically unobserved (early) pregnancy loss rate.

Beyond the issue of causality, several important questions remained unanswered. Delayed effects, or in other words, the potential shift in the timing of pregnancy loss were previously not considered. However, it would be important to know whether a higher number of fetal losses after exposure to hot weather is due to a "genuine" increase in the risk of spontaneous fetal loss or it is caused a forward shift of some pregnancy losses that would have occurred later. Mostly due to the small sample sizes, differences between subgroups of the population could not be examined in the epidemiological literature. From a public policy point of view, identifying the most vulnerable groups is essential and helps to plan effective adaptation and mitigation strategies. Finally, due to climate change, prolonged exposure to heat will rise fast in the following decades. Yet, no study has provided estimates on the impacts of climate change on the risk of miscarriage/stillbirth, even though the quantification of consequences of future temperature changes is fundamental for effective policymaking. In sum, there is a clear need to provide causal evidence on the effect of temperature exposure on spontaneous pregnancy losses and forecast the potential impact of climate change.

Here, we analyze the effect of temperature exposure on the spontaneous pregnancy loss rate and project the impact of climate change. We use administrative data from Hungary with complete coverage of the clinically observed spontaneous pregnancy losses between 1984 and 2018. This dataset contains information on almost 600,000 pregnancy losses. We estimate the causal effects of temperature using data on weekly spontaneous pregnancy loss rates and exploiting the random year-to-year variation in the temperature exposure. We allow for a non-linear relationship between temperature and the pregnancy loss rate by using eight temperature categories representing different daily mean temperatures.

We show that hot days, compared to a mild temperature, cause an increase in the spontaneous pregnancy loss rate, whereas cold temperatures slightly decrease it. For example, a day with >25 °C daily mean temperature increases the pregnancy loss rate by 0.21 losses or 1.4%, compared to a day with 10–15 °C. The effect of heat exposure is especially strong in the first half of the pregnancy (fetal losses in the first twenty weeks of gestation) and among women with less than high school education. Importantly, the estimated changes do not seem to be caused by the temporal displacement of some pregnancy losses, which means that exposure to heat and cold alters the outcome of some pregnancies. Combining the historical effects with outputs of thirty climate models, we show that climate change will increase the spontaneous pregnancy loss rate in the 21st century. The spontaneous pregnancy loss rate is projected to increase especially strongly in the summer period due to climate change.

Our paper contributes to the existing literature in several ways. First, it provides evidence on the causal effects of temperature on spontaneous pregnancy losses. Second, as our data covers all spontaneous pregnancy losses during the whole pregnancy, we can examine which period of the pregnancy is most sensitive to exposure to heat and cold. The impacts are directly comparable to each other because they are produced by the very same empirical approach and dataset. Third, we estimate not only immediate effects but also delayed effects. This allows us to check whether exposure to heat simply shifts forward the date of some pregnancy losses or changes the outcome of pregnancies (from live birth/induced abortion to miscarriage/stillbirth). Fourth, as we have a rich dataset with information on hundreds of thousands of spontaneous pregnancy losses, the heterogeneity of the effects of temperature can be analyzed. Finally, we project the impacts of climate change on the overall pregnancy loss rate and show how the impacts vary across seasons.

2. Relationship between temperatures and the pregnancy loss rate

2.1. Data

2.1.1. Spontaneous pregnancy losses

The source of the pregnancy loss data is the registries of the Hungarian Central Statistical Office (HCSO). These administrative datasets contain every spontaneous pregnancy loss (miscarriages and stillbirths, including ectopic and molar pregnancy) recorded by the Hungarian healthcare system between 1984 and 2018. Among others, the datasets contain information on the length of pregnancy (measured in completed weeks).

We exclude pregnancy losses with missing information on gestational age or on the exact day of the pregnancy loss event, as well as pregnancy losses with non-Hungarian or unknown places of residence (less than 1% of all cases in total). Our final sample covers 590,872 pregnancy losses between 1984 and 2018.

The outcome variable of this study is the pregnancy loss rate. It is defined as the number of pregnancy losses in a given county (NUTS 3 region) per week per 100,000 women aged 15–44. The county is defined by the women's place of residence. The number of women (at the beginning of the year) for every year and county comes from the HCSO. These population numbers are assigned to the first weeks of the year and the unobserved county–week numbers are calculated by linear interpolation. Each year is divided into fifty-two weeks, therefore calendar week 52 is eight days long (except in leap years, when it lasts nine days).

Figure A1 in the Supplementary Materials shows the spatial differences in the average spontaneous pregnancy loss rate in our sample period (1984–2018).

2.1.2. Weather

Weather data comes from the European Climate Assessment & Dataset project (Cornes et al., 2018). The E–OBS 23.1e dataset provides information on daily temperatures, precipitation, relative humidity, and global radiation level for Europe with a spacing of 0.1° × 0.1° in regular latitude/longitude coordinates from 1950 to 2020. We use the mean temperature as the main right-hand-side variable. In the first step, we calculated a daily temperature measure for each county-day pair. As we are interested in the non-linear impact of temperature, each day is classified into one of the following temperature categories: below −5 °C, −5–0 °C, 0–5 °C, 5–10 °C, 10–15 °C, 15–20 °C, 20–25 °C, over 25 °C. Finally, we construct weekly level measures from the daily records. This county-week level dataset can be matched to the fetal death data. To give an insight into regional differences in temperature, Figure A2 in the Supplementary Materials shows the annual average number of days with a mean temperature above 25 °C by county.

As control variables, we use a series of binary indicators that shows the weekly number of days with different precipitation, relative humidity, and global radiation levels (see Table A1 in the Supplementary Materials).

2.2. Methods

To examine the relationship between temperature and the pregnancy loss rate, we estimate the following equation:

$$Y_{cyw} = \sum_{j} \beta^{j} T^{j}_{cyw} + \gamma X_{cyw} + \delta_c + \theta_y + \lambda_w + \varphi^{'}_{w} \times y + \varphi^{''}_{w} \times y^2 + \varepsilon_{cyw} \qquad (1)$$

where Y is the spontaneous pregnancy loss rate in county c in year y and calendar week w. T is a vector of temperature variables indicating the count of days in that week when the daily mean temperature falls in temperature bin j, from ≤−5 °C to >25 °C (the intermediate categories are 5 °C wide). In the analysis, the temperature bin of 10–15 °C is the omitted category. When every day in a given week falls into the same temperature bin, one of the T variables has a value of seven, while the other temperature variables have a value of zero.[1]

X represents the controls: (i) the number of days with different amounts of daily precipitation (0 mm, 0–3 mm, 3–5 mm, 5–10 mm, over 10 mm), (ii) the number of days with different relative humidity (≤50%, 50–60%, 60–70%, 70–80%, 80–90%, >90%), (iii) the number of days with different levels of mean hourly global radiation (≤25 W/m^2, 25–50 W/m^2, 50–100 W/m^2, 100–150 W/m^2, 150–200 W/m^2, 200–250 W/m^2, 250–300 W/m^2, >300 W/m^2), (iv) share of non-working days, and (v) an indicator whether the last week of the year is eight- or nine-day long. The descriptive statistics of the dependent and temperature variables are shown in Table 1, whereas Table A1 in the Supplementary Materials summarizes all variables.

County fixed effects (δ) control for time-invariant differences in spontaneous pregnancy loss rates across counties. Year fixed effects (θ) absorb common shocks at the year level. Calendar week fixed effects (λ) account for seasonal differences in pregnancy loss rates. In

[1] Except in the last calendar week, when the maximum of the temperature variables is eight (or nine in leap years).

Table 1
Descriptive statistics.

Variable	Mean	SD	Min	Max	N
Spontaneous pregnancy loss rate	15.4	4.5	0.0	45.9	36,400
N of days per week with a mean temperature					
≤−5 °C	0.2	0.9	0	9	36,400
−5 to 0 °C	0.7	1.5	0	8	36,400
0–5 °C	1.1	1.9	0	9	36,400
5–10 °C	1.1	1.8	0	7	36,400
10–15 °C	1.2	1.9	0	7	36,400
15–20 °C	1.4	2.1	0	7	36,400
20–25 °C	1.0	1.9	0	7	36,400
>25 °C	0.2	0.9	0	7	36,400

Units of observations: county by year by week. Weighted by the counties' average female population size (aged 15–44) between 1984 and 2018. The spontaneous pregnancy loss rate is defined as the number of spontaneous pregnancy losses per week per 100,000 women aged 15–44. Each year is divided into 52 weeks, therefore calendar week 52 is eight days long (except in leap years, when it lasts nine days).

addition, we allow seasonality to change over time by adding calendar-week-specific quadratic time trends (φ). The inclusion of these fixed effects means that the effects of temperatures on the spontaneous pregnancy loss rate are identified from the random year-to-year variation in the temperature exposure after adjusting for fixed geographic differences, seasonality, and its change over time, as well as for common shocks to pregnancy loss rates at the year level.

Regressions are weighted by the counties' average female population size (aged 15–44) between 1984 and 2018. Standard errors are clustered by county.

To study the dynamics of the temperature-pregnancy loss rate relationship, we add lagged weather variables. This specification allows us to investigate the potential shift in the timing of pregnancy losses after exposure to cold/hot weather. By including the lagged temperature variables, we can answer the important question of whether increasing temperature only causes some pregnancy losses to shift forwards by a few weeks, or it changes the outcome of some pregnancies and increases the risk of pregnancy loss.

$$Y_{cyw} = \sum_j \beta_0^j T_{cyw}^j + \sum_j \beta_1^j T_{c(yw-1)}^j + \sum_j \beta_2^j T_{c(yw-2)}^j + \gamma X_{cyw} + \delta_c + \theta_y + \lambda_w + \varphi_w^{'} \times y + \varphi_w^{''} \times y^2 + \varepsilon_{cyw} \quad (2)$$

In this specification, we allow pregnancy loss rates at time *t* to be affected by the lagged temperature (and the other weather variables) up to 2 weeks, but as a sensitivity test, we experiment with additional lags (see later). (X includes the lagged precipitation, humidity, and radiation variables.) Coefficients β_0, β_1, and β_2 show the effect of temperature on current and future pregnancy loss rates (up to 2 weeks after the temperature exposure) (Stock and Watson, 2015).

2.3. Results

The effects of temperature exposure are summarized in Fig. 1. We find that an additional >25 °C day increases the weekly pregnancy loss rate by 0.21 losses per 100,000 women aged 15–44 years, compared to a 10–15 °C day. This reflects an increase of 1.4% relative to the average weekly pregnancy loss rate (15.4). The effect of a 20–25 °C and a 15–20 °C day is estimated to be 0.09 and 0.05 losses (or 0.6% and 0.3%), respectively. The coefficients of the colder temperature bins are usually negative, but some of them are practically equal to zero. They range between −0.08 and −0.03. In general, the impact of temperature exposure seems to be non-linear. Hot weather increases the pregnancy loss rate, whereas cold temperatures decrease it. Importantly, the latter impacts are not particularly different from each other.

To put these estimates into context, we calculate the predicted difference in pregnancy loss rate between the coldest and warmest week of July in our sample. The hottest week had seven days with a mean temperature >25 °C, while the coldest week had five days with a mean temperature of 10–15 °C and two days with a mean temperature of 15–20 °C. The difference between these two weeks is 1.35 pregnancy losses per 100,000 women aged 15–44 years. In other words, pregnancy loss rate in an unusually hot summer week is 0.30 standard deviations higher than in an unusually cold summer week.[2]

We test the sensitivity of the estimations using alternative model specifications. We experiment with alternative sets of fixed effects, time trends (Table A2, Supplementary Materials), and calculation of standard errors (Table A3, Supplementary Materials). We use 3°C-wide temperature bins, where the lowest category is ≤ −6 °C, and the highest category is > 27 °C (Figure A3, Supplementary Materials). None of these changes influence the conclusions, but the latter result suggests that the impact of extreme heat is disproportionally harmful. Between the categories 6–9 °C and 24–27 °C, the impact of temperature seems to be linear; each additional 3 °C warming has a similar marginal effect. But the impact of a >27 °C day is much stronger than the impact of a 24–27 °C day (0.25 vs 0.13 losses).

As a falsification test, the temperature and other weather variables are replaced with weather data that were measured exactly one

[2] The difference between an unusually hot summer week (seven days with a mean temperature >25 °C) and an unusually cold winter week (seven days with a mean temperature ≤−5 °C) is 1.64 pregnancy losses per 100,000 women aged 15–44 years or 0.36 standard deviations.

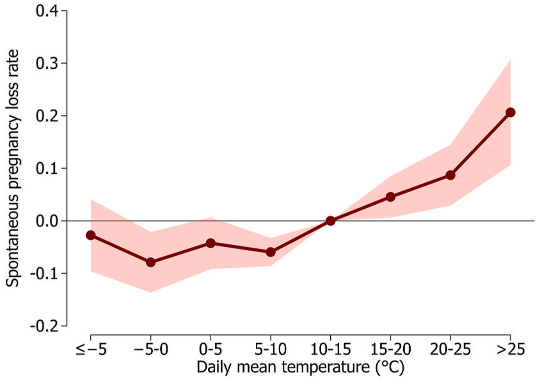

Fig. 1. The impact of temperature exposure on the spontaneous pregnancy loss rate.
The estimations are based on Eq. (1). The shaded area represents 95% confidence intervals. The outcome variable is the spontaneous pregnancy loss rate, which is defined as the number of spontaneous pregnancy losses per week per 100,000 women aged 15–44. The model has county, year, and calendar week fixed effects and calendar week-specific quadratic time trends. Precipitation, relative humidity, global radiation level, the share of non-working days, and leap years are controlled for. The regressions are weighted by the counties' average female population size (aged 15–44) between 1984 and 2018. Standard errors are clustered by county.

year later (Fig. 2). The idea is that the spontaneous pregnancy loss rate could not have been influenced by temperature in the distant future, consequently, we expect to see zero coefficients in this regression. The results strengthen the credibility of the baseline estimates: the estimated effects are not only statistically insignificant but practically zero for all temperature bins.

We also examine which period of the pregnancy is most sensitive to exposure to heat. We calculate spontaneous pregnancy loss rates that count clinically observed pregnancy losses occurring between (i) 0 and 7, (ii) 8 and 11, (iii) 12 and 20, or (iv) 21 or more completed pregnancy weeks. Using these four pregnancy loss rates as dependent variables, we re-estimate Eq. (1). As the average levels of the four pregnancy loss rates are different, we present the results as percentage impact. Although the estimates are sometimes noisy, the point estimates suggest that exposure to a hot day has a stronger impact in the first half of the pregnancy, especially at the end of the first trimester (Fig. 3). The spontaneous pregnancy loss rate is increased by 0.9% due to exposure to a >25 °C day before the eighth completed pregnancy week, whereas the corresponding figure is 1.9% between the eighth and eleventh completed pregnancy weeks. For pregnancy losses between weeks 12 and 20, we find that the estimations are less precise: the impact of hot weather is 1.2% with a wide confidence interval. For pregnancy losses after 20 completed weeks, the estimations are noisy. Nevertheless, temperatures seem to have less important effects on late pregnancy loss rates.

Studying the dynamics of the temperature-fetal loss relationship, we added the weather indicators of the previous two weeks. In general, we find that the effects of the lagged temperature variables are weak and not different from zero, whereas the immediate impacts are unchanged (Fig. 4). It suggests that the immediate increase in the pregnancy loss rate following hot temperatures is not driven by the near-term displacement of some pregnancy losses. Increasing temperature changes the outcomes of some pregnancies (from live birth or induced abortion to spontaneous pregnancy loss). This conclusion does not change even if one or two extra lags are included (Figure A4 and Figure A5, Supplementary Materials).

We also examine the heterogeneity of the impacts of temperatures. First, we calculate pregnancy loss rates for women aged 30 or younger and women aged 31 or older. We do not find any meaningful differences (Figure A6, Supplementary Materials). The percentage impacts are very similar for younger and older women. However, we find differences by education (Figure A7, Supplementary Materials). In this exercise, high school graduates are considered as highly educated individuals. We restricted the sample to women aged 19 and older, as younger people may not have enough time to get their high school leaving certificates. We use census information on the share of low and high educated women aged 19–44 by county (population census 1980, 1990, 2001, and 2011) to calculate the number of low and high educated women and the spontaneous pregnancy loss rates for each year between 1984 and 2018. The estimations indicate that the spontaneous pregnancy loss rate of the low educated women is more sensitive to extreme heat than the spontaneous pregnancy loss rate of the women with high education levels. Although confidence intervals are wide and the difference does not reach the threshold of statistical significance, the point estimates are twice as large for women with low education. The impact of a >25 °C day is 1.4% in the low education group and 0.7% in the high education group. The effects of the 20–25 °C and 15–20 °C days are also slightly higher among women with low education, while the point estimates of the other temperature bins are virtually identical in the two groups. The observed differences are not unexpected, as women with low level of education usually have a limited capacity to cope with the impacts of hot weather. Disadvantaged women are more likely to live in apartments and houses that are not protected against excessive heat stress. They are also more likely to be employed in physically demanding occupations where the work is primarily performed outdoors. Consequently, hot temperatures can have a stronger effect on the low educated.

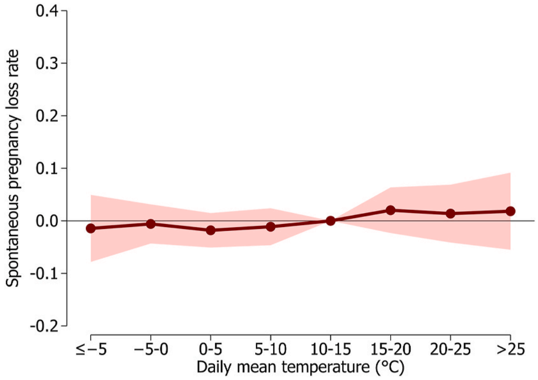

Fig. 2. Falsification test with temperature variables one year later.
Temperature and other weather variables are replaced with weather data measured exactly one year later. The shaded area represents 95% confidence intervals. The outcome variable is the spontaneous pregnancy loss rate, which is defined as the number of spontaneous pregnancy losses per week per 100,000 women aged 15–44. The model has county, year, and calendar week fixed effects and calendar week-specific quadratic time trends. Precipitation, relative humidity, global radiation level, the share of non-working days, and leap years are controlled for. The regressions are weighted by the counties' average female population size (aged 15–44) between 1984 and 2018. Standard errors are clustered by county.

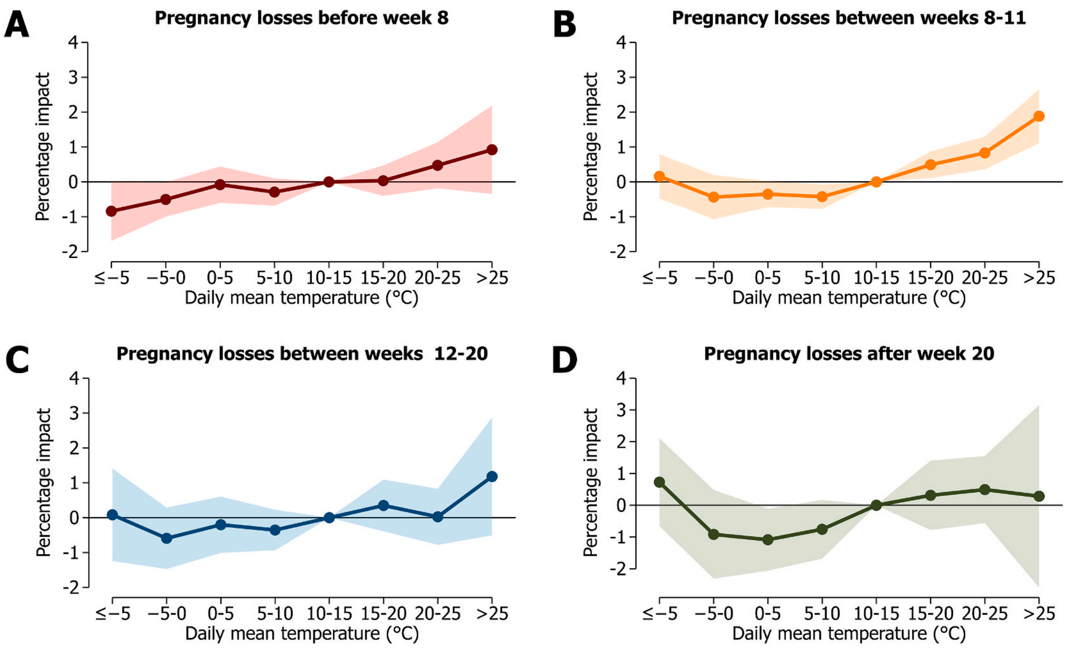

Fig. 3. The impact of temperature exposure on the spontaneous pregnancy loss rate by gestation length.
The shaded area represents 95% confidence intervals. The outcome variable is the spontaneous pregnancy loss rates, which is defined as the number of spontaneous pregnancy losses occurring between (i) 0 and 7, (ii) 8 and 11, (iii) 12 and 20, or (iv) 21 or more completed pregnancy weeks per week per 100,000 women aged 15–44. The model has county, year, and calendar week fixed effects and calendar week-specific quadratic time trends. Precipitation, relative humidity, global radiation level, the share of non-working days, and leap years are controlled for. The regressions are weighted by the counties' average female population size (aged 15–44) between 1984 and 2018. Standard errors are clustered by county.

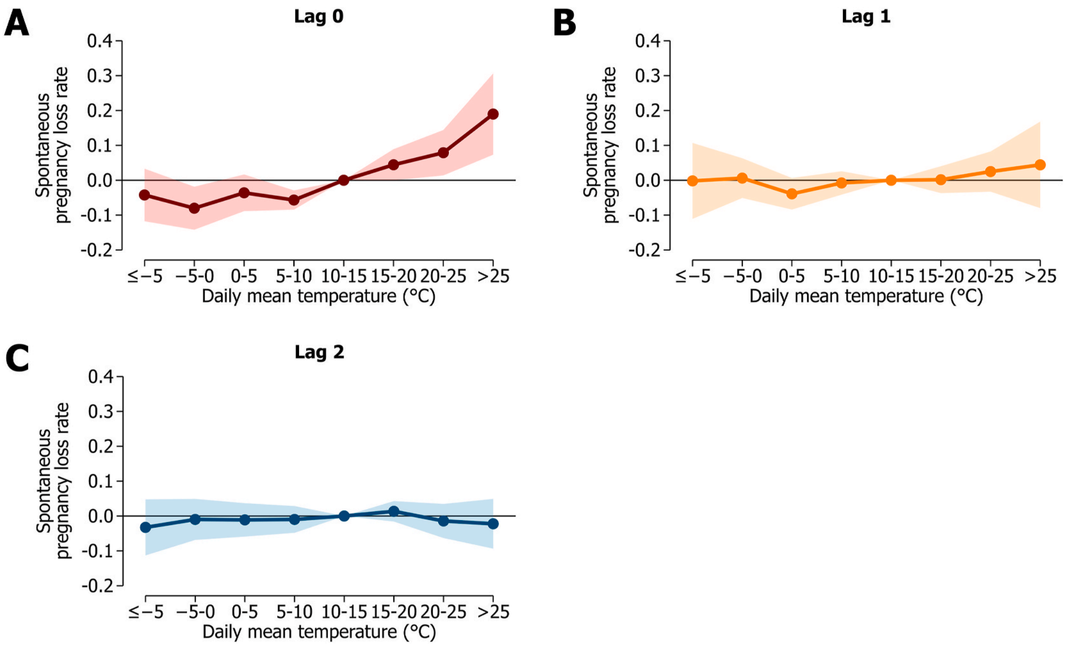

Fig. 4. The immediate and delayed impacts of temperature exposure on the spontaneous pregnancy loss rate.
The estimations are based on Eq. (2). The shaded area represents 95% confidence intervals. The outcome variable is the spontaneous pregnancy loss rate, which is defined as the number of spontaneous pregnancy losses per week per 100,000 women aged 15–44. The model has county, year, and calendar week fixed effects and calendar week-specific quadratic time trends. Precipitation, relative humidity, global radiation level, the share of non-working days, and leap years are controlled for. The regressions are weighted by the counties' average female population size (aged 15–44) between 1984 and 2018. Standard errors are clustered by county.

3. The impacts of climate change

3.1. Data

We use projections of thirty climate models[3] and two Shared Socioeconomic Pathways-based (SSPs) scenarios of the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) dataset to calculate the impact of climate change. The NEX-GDDP-CMIP6 dataset provides daily temperature projections for 2015–2100 and retrospectively simulated temperature data for the period 1950–2014. The spatial resolution of the projections is 0.25° × 0.25°. We use projected temperature changes under the SSP5-8.5 and SSP2-4.5 scenarios (O'Neill et al., 2016). These are state-of-the-art scenarios for modeling climate change. The first one is a worst-case, high-emission scenario that assumes a fossil-fuel based development during the remaining decades of the 21st century. Consequently, the CO_2 concentration will rise throughout the 21st century in this scenario and the average global surface temperature is very likely to be higher by 3.3°C–5.7 °C at the end of the century, compared to 1850–1900 (IPCC, 2021). Although it is a highly unlikely scenario, it can be regarded as the upper bound of the potential warming and offers important information for policymaker about the severity of the worst-case impacts. The second scenario is a more optimistic one that is often labeled as a "middle-of-the-road" scenario. It assumes that climate protection measures will be taken, the CO_2 emission will decline after the 2050s and CO_2 concentration will stabilize by 2100. The warming is projected to be 2.1–3.4 °C in this scenario (IPCC, 2021).

We calculated the within-model changes in the daily temperature distribution represented by the eight temperature categories for each decade between 2020 and 2099. The 1990–2014 period serves as a baseline. The daily data are calculated by averaging the mean temperature for each day of a given decade over grid points within Hungary. Using the daily data, we created an annual distribution of the mean temperature by decades.

3.2. Methods

The impacts of climate change are projected by combining the estimated effects of temperature with the projected within-model changes in temperature distribution in the 21st century for Hungary. Specifically, β coefficients in Eq. (1) are multiplied by the

[3] ACCESS-CM2, ACCESS-ESM1-5, BCC-CSM2-MR, CanESM5, CESM2, CESM2-WACCM, CMCC-CM2-SR5, CMCC-ESM2, CNRM-CM6-1, CNRM-ESM2-1, EC-Earth3, EC-Earth3-Veg-LR, FGOALS-g3, GFDL-CM4-gr1, GFDL-CM4-gr2, GFDL-ESM4, GISS-E2-1-G, IITM-ESM, INM-CM4-8, INM-CM5-0, IPSL-CM6A-LR, KIOST-ESM, MIROC6, MIROC-ES2L, MPI-ESM1-2-HR, MPI-ESM1-2-LR, MRI-ESM2-0, NESM3, NorESM2-LM, NorESM2-MM.

projected temperature changes for each decade between 2020 and 2099. Formally:

$$\Delta Y_{pmd} = \sum_j \beta^j \Delta T^j_{pmd} \tag{3}$$

where p stands for the SSPs, m denotes the climate model, and d denotes the decade. ΔT is a vector that shows the projected change in the annual number of days with different mean temperatures between 1990 and 2014 and the decades in the 21st century starting with the 2020s (Table A4 in the Supplementary Materials shows the average values of the thirty climate models). The β coefficients are from Eq. (1). ΔY is the projected change in the spontaneous pregnancy loss rate. By using outputs from thirty climate models and two SSPs, we account for climate uncertainty, but we also account for regression uncertainty (Burke et al., 2015) by bootstrapping the β coefficient estimates of Eq. (1) (500 times, sampling with replacement). It means that we have 30,000 projections (15,000 for both climate scenarios).

We not only project the overall impact of climate change but also calculate the impacts by season (denoted by s). In this exercise, we take the season-specific temperature changes and, as before, we multiple them with the estimated effects of temperatures[4]:

$$\Delta Y_{pmds} = \sum_j \beta^j \Delta T^j_{pmds} \tag{4}$$

For the projections of the impacts of climate change, we assume that the future relationship between temperature and the pregnancy loss rate (β coefficients) will be the same as in the past. Although future adaptation might change the estimated relationship, without credible empirical estimates, we cannot incorporate it into the projections. In addition, we see little signs of sizable adaptation in our sample (Figure A8 in the Supplementary Materials). It should also be noted that the effects of previously unexperienced extreme temperature events cannot be considered in these projections. The observed historical relationship between temperature and pregnancy losses inadequately informs us on the effects of extreme warming that are beyond human experience. Extreme heat in the future might have stronger effect than the estimated effects of the highest temperature category in our sample. Besides, future warming might be accompanied by changes that occur only once critical thresholds are crossed (e.g., changing precipitation patterns, new pathogens and vectors, intensification of storms, drinking water shortage, etc.). These changes might affect pregnancy losses beyond the direct impact of temperature changes that we can consider.

3.3. Results

Fig. 5 summarizes the projected impacts in percentage terms. Each yellow line represents an individual projection. The red lines are the median of the projected impact. On the right side of the graph, we present medians, interquartile ranges, and the full range of the projections for the last decade. In general, the risk of pregnancy loss is projected to increase in the 21st century in both SSP scenarios. For the last decade, the median projections suggest an increase of 2.2% in the worst-case climate scenario and 1.1% in the more optimistic climate scenario. The projections range from 0.3 to 4.6% (SSP5-8.5) and from 0.1 to 2.9% (SSP2-4.5).

These values show the overall impacts; however, climate change affects the seasons unevenly. Calculating the impacts separately for each season at the end of the 21st century, we find that the risk of spontaneous pregnancy loss is unaffected during winter, whereas in the spring, autumn, and especially in the summer months, it is projected to increase substantially (Fig. 6). During summer, the median projection is an increase of 4.3% in SSP5-8.5 (the full range of the projections is 0.3–9.3%) and 2.3% in SSP2-4.5 (with a range of 0.2–6.6%).

4. Conclusions

Using administrative data for a 35-year-long period, we provide evidence that exposure to hot temperatures increases the spontaneous pregnancy loss rate, whereas cold temperatures decrease it in a European country with a continental climate. The effect of extreme heat is especially strong. Compared to a day with a mean temperature of 10–15 °C, a >25 °C day increases the weekly pregnancy loss rate by 1.4%. Studying the dynamics of the temperature-pregnancy loss relationship, we show that increasing temperature changes the outcome of some pregnancies and not simply the timing of some spontaneous pregnancy losses. Exposure to a hot day appears to have a slightly stronger effect on early pregnancy loss rates, and among women with low education.

Combining the estimated temperature effects with temperature projections of thirty climate models in two SSP scenarios, we show that climate change will increase the risk of pregnancy loss in the 21st century. Considering the impacts on the annual rate of pregnancy loss, the projections range between 0.3 and 4.6% in the SSP5-8.5 and 0.1–2.9% in the SSP2-4.5 scenario. However, the risk of pregnancy loss is projected to be especially elevated during summer.

The estimations of this paper imply that policymakers should consider the threat of increased risk of fetal loss when designing strategies to mitigate the impacts of heat and climate change. Individual actions and avoidance behavior that minimize health risks might be incited by raising public awareness of the harmful effects of heat and by implementing a warning system that notifies pregnant women about extreme heat. It might be especially important for women (and their partners) who are close to the end of their

[4] Calendar weeks 10–22 are the spring weeks, calendar weeks 23–35 are the summer weeks, calendar weeks 36–48 are the autumn weeks, whereas calendar weeks 1–9 and 49–52 are the winter weeks.

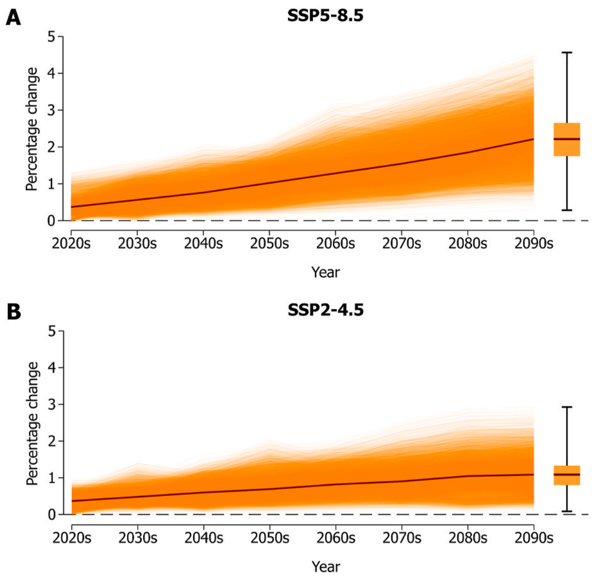

Fig. 5. The projected impact of climate change on the risk of spontaneous pregnancy loss.
The impacts are calculated using the projected within-model differences in temperature distribution between 1990 and 2014 and each decade in the 21st century and the historical relationship between the spontaneous pregnancy loss rate and temperature from Eq. (1) (estimated by 500 bootstrap samples). Yellow lines are the individual projections, red lines represent the medians. The box plots show the distribution of the projections for the 2090s: the medians, the interquartile ranges, and the full ranges of the projections.

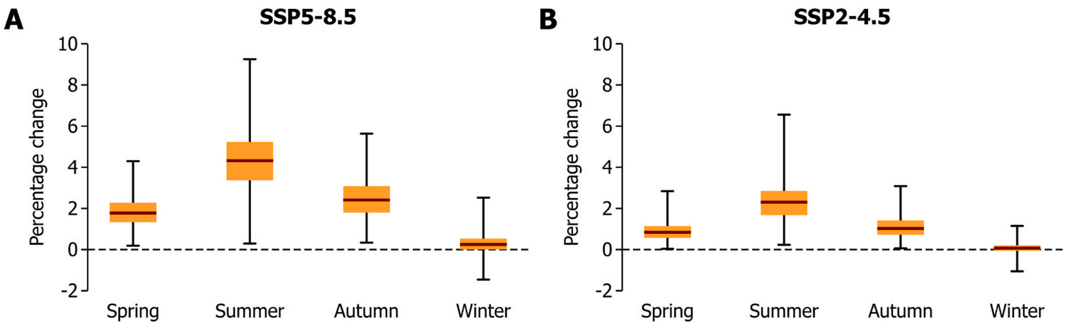

Fig. 6. The impact of climate change on the risk of spontaneous pregnancy loss by season for 2090–2099.
The impacts are calculated using the projected within-model differences in temperature distribution between 1990-2014 and 2090–2099, and the historical relationship between the spontaneous pregnancy loss rate and temperature from Eq. (1) (estimated by 500 bootstrap samples). The box plots show the distribution of the projections for the 2090s: the medians, the interquartile ranges, and the full range of the projections.

reproductive life. As the risk of fetal loss increases sharply (and the chance that pregnancy ends in a live birth decreases sharply) with maternal age (Quenby et al., 2021; Regan and Rai, 2000), the cost of unintended termination of pregnancy due to temperature-induced spontaneous fetal loss might be much higher for women at their late 30s and older who plan to have a child. As the age of mothers at childbirth is increasing worldwide, the non-negligible consequences of heat stress during pregnancy will be a problem for more and more families.

Our results have implications for the broader literature as well. Changing spontaneous fetal loss rate following in utero exposure to heat or cold implies a change in the composition of fetuses that survive to live birth. The survivors represent a selected sample of conceptions that are affected by the temperature shocks. Importantly, increased temperature, like other adverse events, is likely to remove fetuses with below-average health which has been recognized by the literature (Almond and Currie, 2011; Bozzoli et al., 2009; Bruckner and Catalano, 2018; Catalano et al., 2012). As mentioned before, several papers examine the impacts of temperature exposure during pregnancy and climate change on health at birth (e.g. Barreca and Schaller, 2020; Deschênes et al., 2009; Hajdu and Hajdu, 2021a), while others analyze the effects on long-term outcomes (Fishman et al., 2019; Hu and Li, 2019; Isen et al., 2017; Wilde et al., 2017). Our estimates provide hard evidence that these estimations are likely to be lower bounds of the actual impact ("scarring" effect) due to a temperature-induced in utero selection. However, the extent of the bias is unclear and remains a subject for future studies.

Declaration of competing interest

Authors declare no competing interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jeem.2022.102771.

References

Almond, D., Currie, J., 2011. Killing me softly: the fetal origins hypothesis. J. Econ. Perspect. 25, 153–172. https://doi.org/10.1257/jep.25.3.153.

Andalón, M., Azevedo, J.P., Rodríguez-Castelán, C., Sanfelice, V., Valderrama-González, D., 2016. Weather shocks and health at birth in Colombia. World Dev. 82, 69–82. https://doi.org/10.1016/j.worlddev.2016.01.015.

Asamoah, B., Kjellstrom, T., Östergren, P.-O., 2018. Is ambient heat exposure levels associated with miscarriage or stillbirths in hot regions? A cross-sectional study using survey data from the Ghana Maternal Health Survey 2007. Int. J. Biometeorol. 62, 319–330. https://doi.org/10.1007/s00484-017-1402-5.

Auger, N., Fraser, W.D., Smargiassi, A., Bilodeau-Bertrand, M., Kosatsky, T., 2017. Elevated outdoor temperatures and risk of stillbirth. Int. J. Epidemiol. 46, 200–208. https://doi.org/10.1093/ije/dyw077.

Banerjee, R., Maharaj, R., 2020. Heat, infant mortality, and adaptation: evidence from India. J. Dev. Econ. 143, 102378 https://doi.org/10.1016/j.jdeveco.2019.102378.

Barreca, A., Clay, K., Deschenes, O., Greenstone, M., Shapiro, J.S., 2016. Adapting to climate change: the remarkable decline in the US temperature-mortality relationship over the twentieth century. J. Polit. Econ. 124, 105–159. https://doi.org/10.1086/684582.

Barreca, A., Deschenes, O., Guldi, M., 2018. Maybe next month? Temperature shocks and dynamic adjustments in birth rates. Demography 55, 1269–1293. https://doi.org/10.1007/s13524-018-0690-7.

Barreca, A., Schaller, J., 2020. The impact of high ambient temperatures on delivery timing and gestational lengths. Nat. Clim. Change 10, 77–82. https://doi.org/10.1038/s41558-019-0632-4.

Barreca, A.I., 2012. Climate change, humidity, and mortality in the United States. J. Environ. Econ. Manag. 63, 19–34. https://doi.org/10.1016/j.jeem.2011.07.004.

Basu, R., Sarovar, V., Malig, B.J., 2016. Association between high ambient temperature and risk of stillbirth in California. Am. J. Epidemiol. 183, 894–901. https://doi.org/10.1093/aje/kwv295.

Blencowe, H., Cousens, S., Jassir, F.B., Say, L., Chou, D., Mathers, C., Hogan, D., Shiekh, S., Qureshi, Z.U., You, D., Lawn, J.E., 2016. National, regional, and worldwide estimates of stillbirth rates in 2015, with trends from 2000: a systematic analysis. Lancet Global Health 4, e98–e108. https://doi.org/10.1016/S2214-109X(15)00275-2.

Bozzoli, C., Deaton, A., Quintana-Domeque, C., 2009. Adult height and childhood disease. Demography 46, 647–669. https://doi.org/10.1353/dem.0.0079.

Bruckner, T.A., Catalano, R., 2018. Selection in utero and population health: theory and typology of research. SSM - Population Health 5, 101–113. https://doi.org/10.1016/j.ssmph.2018.05.010.

Bruckner, T.A., Modin, B., Vågerö, D., 2014. Cold ambient temperature in utero and birth outcomes in Uppsala, Sweden, 1915–1929. Ann. Epidemiol. 24, 116–121. https://doi.org/10.1016/j.annepidem.2013.11.005.

Burke, M., Dykema, J., Lobell, D.B., Miguel, E., Satyanath, S., 2015. Incorporating climate uncertainty into estimates of climate change impacts. Rev. Econ. Stat. 97, 461–471. https://doi.org/10.1162/REST_a_00478.

Cacciatore, J., 2013. Psychological effects of stillbirth. Seminars in Fetal and Neonatal Medicine, Palliative Care and End-of-Life Decisions 18, 76–82. https://doi.org/10.1016/j.siny.2012.09.001.

Carleton, T., Jina, A., Delgado, M., Greenstone, M., Houser, T., Hsiang, S., Hultgren, A., Kopp, R.E., McCusker, K.E., Nath, I., Rising, J., Rode, A., Seo, H.K., Viaene, A., Yuan, J., Zhang, A.T., 2022. Valuing the global mortality consequences of climate change accounting for adaptation costs and benefits. Q. J. Econ. 137, 2037–2105. https://doi.org/10.1093/qje/qjac020.

Carleton, T.A., Hsiang, S.M., 2016. Social and economic impacts of climate. Science 353, aad9837. https://doi.org/10.1126/science.aad9837.

Catalano, R., Goodman, J., Margerison-Zilko, C.E., Saxton, K.B., Anderson, E., Epstein, M., 2012. Selection against small males in utero: a test of the Wells hypothesis. Hum. Reprod. 27, 1202–1208. https://doi.org/10.1093/humrep/der480.

Cohen, F., Dechezleprêtre, A., 2022. Mortality, temperature, and public health provision: evidence from Mexico. Am. Econ. J. Econ. Pol. 14, 161–192. https://doi.org/10.1257/pol.20180594.

Conte Keivabu, R., Cozzani, M., 2022. Extreme heat, birth outcomes, and socioeconomic heterogeneity. Demography 59, 1631–1654. https://doi.org/10.1215/00703370-10174836.

Cornes, R.C., Schrier, G. van der, Besselaar, E.J.M. van den, Jones, P.D., 2018. An ensemble version of the E-OBS temperature and precipitation data sets. J. Geophys. Res. Atmos. 123, 9391–9409. https://doi.org/10.1029/2017JD028200.

Davenport, F., Dorélien, A., Grace, K., 2020. Investigating the linkages between pregnancy outcomes and climate in sub-Saharan Africa. Popul. Environ. 41, 397–421. https://doi.org/10.1007/s11111-020-00342-w.

Dell, M., Jones, B.F., Olken, B.A., 2014. What do we learn from the weather? The new climate-economy literature. J. Econ. Lit. 52, 740–798. https://doi.org/10.1257/jel.52.3.740.

Deschênes, O., Greenstone, M., 2011. Climate change, mortality, and adaptation: evidence from annual fluctuations in weather in the US. Am. Econ. J. Appl. Econ. 3, 152–185. https://doi.org/10.1257/app.3.4.152.

Deschênes, O., Greenstone, M., Guryan, J., 2009. Climate change and birth weight. Am. Econ. Rev. 99, 211–217. https://doi.org/10.1257/aer.99.2.211.

Deschênes, O., Moretti, E., 2009. Extreme weather events, mortality, and migration. Rev. Econ. Stat. 91, 659–681. https://doi.org/10.1162/rest.91.4.659.

Fishman, R., Carrillo, P., Russ, J., 2019. Long-term impacts of exposure to high temperatures on human capital and economic productivity. J. Environ. Econ. Manag. 93, 221–238. https://doi.org/10.1016/j.jeem.2018.10.001.

Geruso, M., Spears, D., 2018. Heat, Humidity, and Infant Mortality in the Developing World (NBER Working Paper No. 24870). National Bureau of Economic Research. https://doi.org/10.3386/w24870.

Gold, K.J., Sen, A., Hayward, R.A., 2010. Marriage and cohabitation outcomes after pregnancy loss. Pediatrics 125, e1202–e1207. https://doi.org/10.1542/peds.2009-3081.

Grace, K., Verdin, A., Dorélien, A., Davenport, F., Funk, C., Husak, G., 2021. Exploring strategies for investigating the mechanisms linking climate and individual-level child health outcomes: an analysis of birth weight in Mali. Demography 58, 499–526. https://doi.org/10.1215/00703370-8977484.

Ha, S., Liu, D., Zhu, Y., Soo Kim, S., Sherman, S., Grantz, K.L., Mendola, P., 2017. Ambient temperature and stillbirth: a multi-center retrospective cohort study. Environ. Health Perspect. 125 https://doi.org/10.1289/EHP945.

Hajdu, T., Hajdu, G., 2022a. Temperature, climate change, and fertility. In: Zimmermann, K.F. (Ed.), Handbook of Labor, Human Resources and Population Economics. Springer, Cham, pp. 1–25. https://doi.org/10.1007/978-3-319-57365-6_262-1.

Hajdu, T., Hajdu, G., 2022b. Temperature, climate change, and human conception rates: evidence from Hungary. J. Popul. Econ. 35, 1751–1776. https://doi.org/10.1007/s00148-020-00814-1.

Hajdu, T., Hajdu, G., 2021a. Temperature, climate change, and birth weight: evidence from Hungary. Popul. Environ. 43, 131–148. https://doi.org/10.1007/s11111-021-00380-y.

Hajdu, T., Hajdu, G., 2021b. Post-conception heat exposure increases clinically unobserved pregnancy losses. Sci. Rep. 11 https://doi.org/10.1038/s41598-021-81496-x.

Hanlon, W.W., Hansen, C.W., Kantor, J., 2021. Temperature, disease, and death in london: analyzing weekly data for the century from 1866 to 1965. J. Econ. Hist. 81, 40–80. https://doi.org/10.1017/S0022050720000613.

Heutel, G., Miller, N.H., Molitor, D., 2021. Adaptation and the mortality effects of temperature across U.S. Climate regions. Rev. Econ. Stat. 103, 740–753. https://doi.org/10.1162/rest_a_00936.

Hsiang, S., 2016. Climate econometrics. Annual Review of Resource Economics 8, 43–75. https://doi.org/10.1146/annurev-resource-100815-095343.

Hu, Z., Li, T., 2019. Too hot to handle: the effects of high temperatures during pregnancy on adult welfare outcomes. J. Environ. Econ. Manag. 94, 236–253. https://doi.org/10.1016/j.jeem.2019.01.006.

Hug, L., You, D., Blencowe, H., Mishra, A., Wang, Z., Fix, M.J., Wakefield, J., Moran, A.C., Gaigbe-Togbe, V., Suzuki, E., Blau, D.M., Cousens, S., Creanga, A., Croft, T., Hill, K., Joseph, K.S., Maswime, S., McClure, E.M., Pattinson, R., Pedersen, J., Smith, L.K., Zeitlin, J., Alkema, L., 2021. Global, regional, and national estimates and trends in stillbirths from 2000 to 2019: a systematic assessment. Lancet 398, 772–785. https://doi.org/10.1016/S0140-6736(21)01112-0.

IPCC, 2021. Summary for policymakers. In: Climate Change 2021: the Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

Isen, A., Rossin-Slater, M., Walker, R., 2017. Relationship between season of birth, temperature exposure, and later life wellbeing. Proc. Natl. Acad. Sci. USA 114, 13447–13452. https://doi.org/10.1073/pnas.1702436114.

Jarvis, G.E., 2016. Estimating limits for natural human embryo mortality. F1000Res 5, 2083. https://doi.org/10.12688/f1000research.9479.2.

Karlsson, M., Ziebarth, N.R., 2018. Population health effects and health-related costs of extreme temperatures: comprehensive evidence from Germany. J. Environ. Econ. Manag. 91, 93–117. https://doi.org/10.1016/j.jeem.2018.06.004.

Kersting, A., Wagner, B., 2012. Complicated grief after perinatal loss. Dialogues Clin. Neurosci. 14, 187–194. https://doi.org/10.31887/DCNS.2012.14.2/akersting.

Li, S., Chen, G., Jaakkola, J.J.K., Williams, G., Guo, Y., 2018. Temporal change in the impacts of ambient temperature on preterm birth and stillbirth: brisbane, 1994–2013. Sci. Total Environ. 634, 579–585. https://doi.org/10.1016/j.scitotenv.2018.03.385.

Lok, I.H., Neugebauer, R., 2007. Psychological morbidity following miscarriage. Best practice & research clinical obstetrics & gynaecology. Psychological Issues in Obstetrics and Gynaecology 21, 229–247. https://doi.org/10.1016/j.bpobgyn.2006.11.007.

McElroy, S., Ilango, S., Dimitrova, A., Gershunov, A., Benmarhnia, T., 2022. Extreme heat, preterm birth, and stillbirth: a global analysis across 14 lower-middle income countries. Environ. Int. 158, 106902 https://doi.org/10.1016/j.envint.2021.106902.

Mullins, J.T., White, C., 2020. Can access to health care mitigate the effects of temperature on mortality? J. Publ. Econ. 191, 104259 https://doi.org/10.1016/j.jpubeco.2020.104259.

Ngo, N.S., Horton, R.M., 2016. Climate change and fetal health: the impacts of exposure to extreme temperatures in New York City. Environ. Res. 144, 158–164. https://doi.org/10.1016/j.envres.2015.11.016. Part A.

O'Neill, B.C., Tebaldi, C., van Vuuren, D.P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G.A., Moss, R., Riahi, K., Sanderson, B.M., 2016. The scenario model intercomparison project (ScenarioMIP) for CMIP6. Geosci. Model Dev. (GMD) 9, 3461–3482. https://doi.org/10.5194/gmd-9-3461-2016.

Otrachshenko, V., Popova, O., Solomin, P., 2018. Misfortunes never come singly: consecutive weather shocks and mortality in Russia. Econ. Hum. Biol. https://doi.org/10.1016/j.ehb.2018.08.008.

Quenby, S., Gallos, I.D., Dhillon-Smith, R.K., Podesek, M., Stephenson, M.D., Fisher, J., Brosens, J.J., Brewin, J., Ramhorst, R., Lucas, E.S., McCoy, R.C., Anderson, R., Daher, S., Regan, L., Al-Memar, M., Bourne, T., MacIntyre, D.A., Rai, R., Christiansen, O.B., Sugiura-Ogasawara, M., Odendaal, J., Devall, A.J., Bennett, P.R., Petrou, S., Coomarasamy, A., 2021. Miscarriage matters: the epidemiological, physical, psychological, and economic costs of early pregnancy loss. Lancet 397, 1658–1667. https://doi.org/10.1016/S0140-6736(21)00682-6.

Rai, R., Regan, L., 2006. Recurrent miscarriage. Lancet 368, 601–611. https://doi.org/10.1016/S0140-6736(06)69204-0.

Rammah, A., Whitworth, K.W., Han, I., Chan, W., Hess, J.W., Symanski, E., 2019. Temperature, placental abruption and stillbirth. Environ. Int. 131, 105067 https://doi.org/10.1016/j.envint.2019.105067.

Regan, L., Rai, R., 2000. Epidemiology and the medical causes of miscarriage. Best Pract. Res. Clin. Obstet. Gynaecol. 14, 839–854. https://doi.org/10.1053/beog.2000.0123.

Robinson, G.E., 2014. Pregnancy loss. Best practice & research clinical obstetrics & gynaecology. Perinatal Mental Health: Guidance for the Obstetrician-Gynaecologist 28, 169–178. https://doi.org/10.1016/j.bpobgyn.2013.08.012.

Sexton, J., Andrews, C., Carruthers, S., Kumar, S., Flenady, V., Lieske, S., 2021. Systematic review of ambient temperature exposure during pregnancy and stillbirth: methods and evidence. Environ. Res. 197, 111037 https://doi.org/10.1016/j.envres.2021.111037.

Shreffler, K.M., Hill, P.W., Cacciatore, J., 2012. Exploring the increased odds of divorce following miscarriage or stillbirth. J. Divorce & Remarriage 53, 91–107. https://doi.org/10.1080/10502556.2012.651963.

Stock, J.H., Watson, M.W., 2015. Introduction to Econometrics, third ed. Pearson Education.

Strand, L.B., Barnett, A.G., Tong, S., 2012. Maternal exposure to ambient temperature and the risks of preterm birth and stillbirth in brisbane, Australia. Am. J. Epidemiol. 175, 99–107. https://doi.org/10.1093/aje/kwr404.

Sun, S., Spangler, K.R., Weinberger, K.R., Yanosky, J.D., Braun, J.M., Wellenius, G.A., 2019. Ambient temperature and markers of fetal growth: a retrospective observational study of 29 million U.S. Singleton births. Environ. Health Perspect. 127, 067005 https://doi.org/10.1289/EHP4648.

Sun, X., Luo, X., Cao, G., Zhao, C., Xiao, J., Liu, X., Dong, M., Wang, J., Zeng, W., Guo, L., Wan, D., Ma, W., Liu, T., 2020. Associations of ambient temperature exposure during pregnancy with the risk of miscarriage and the modification effects of greenness in Guangdong, China. Sci. Total Environ. 702, 134988 https://doi.org/10.1016/j.scitotenv.2019.134988.

van Oppenraaij, R.H.F., Jauniaux, E., Christiansen, O.B., Horcajadas, J.A., Farquharson, R.G., Exalto, N., on behalf of the ESHRE Special Interest Group for Early Pregnancy (SIGEP), 2009. Predicting adverse obstetric outcome after early pregnancy events and complications: a review. Hum. Reprod. Update 15, 409–421. https://doi.org/10.1093/humupd/dmp009.

Wilcox, A.J., Harmon, Q., Doody, K., Wolf, D.P., Adashi, E.Y., 2020. Preimplantation loss of fertilized human ova: estimating the unobservable. Hum. Reprod. 35, 743–750. https://doi.org/10.1093/humrep/deaa048.

Wilde, J., Apouey, B.H., Jung, T., 2017. The effect of ambient temperature shocks during conception and early pregnancy on later life outcomes. Eur. Econ. Rev. 97, 87–107. https://doi.org/10.1016/j.euroecorev.2017.05.003.

Yu, X., Lei, X., Wang, M., 2019. Temperature effects on mortality and household adaptation: evidence from China. J. Environ. Econ. Manag. 96, 195–212. https://doi.org/10.1016/j.jeem.2019.05.004.